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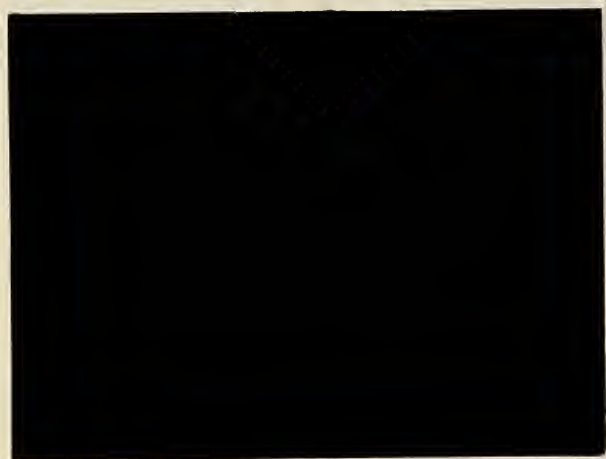
Final Report

THE USE OF FUZZY SETS MATHEMATICS
TO ASSIST PAVEMENT
EVALUATION AND MANAGEMENT

M. Andonyadis
A. G. Altschaeffl
J. L. Chameau



PURDUE UNIVERSITY



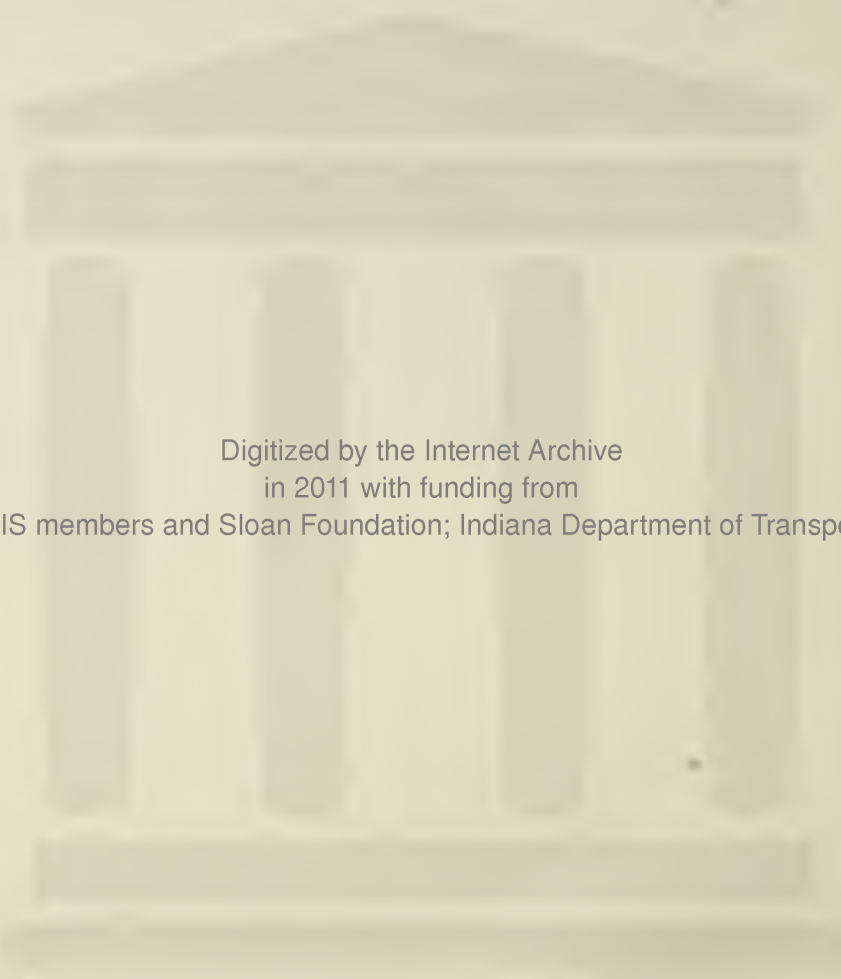
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Final Report

"The Use of Fuzzy Sets Mathematics to Assist
Pavement Evaluation and Management"

To: Harold L. Michael, Director
Joint Highway Research Project

July 2, 1985
revised March 18, 1986

From: A. G. Altschaeffl, P.E.
Research Engineer
and J. L. Chameau,
Research Associate

Project: C-36-63J

File: 9-7-10

Please find attached the Final Report on the HPR Part II Study entitled, "The Use of Fuzzy Sets Mathematics to Assist Pavement Evaluation and Management". Its authors are Mr. M. Andonyadis, A. G. Altschaeffl, and J. L. Chameau of our staff.

This report implements and applies the mathematics of fuzzy sets to the performance data for IDOH pavements. In doing this, the report represents the fulfillment of the objectives of this study. It is companion to the interim report of Gunaratne, et al. (1984), which created the mathematics.

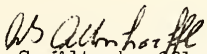
The new scheme being suggested for pavement management is predicated upon the thesis that uncertainty is present and judgment must be applied at various stages of pavement management. The fuzzy sets mathematics can methodically combine subjective information and crisp measurement data.

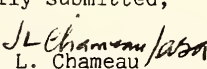
The ranking of pavements is formulated using fuzzy multi-attribute decision-making concepts. To use the new scheme required the one-time development of a knowledge base. At any time thereafter, performance data can be applied to the knowledge base to develop a crisp rank-ordering of pavements according to their maintenance urgency. This report presents the details of the development of the knowledge base using responses from experts to appropriate questionnaires.

Included within this report are suggestions for improvement in the Indiana pavement management program, which could take full advantage of the possibilities offered by this new scheme.

This Final Report is submitted for review and approval as fulfillment of the objectives of this Study.

Respectfully submitted,


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Final Report

"The Use of Fuzzy Sets Mathematics to Assist
Pavement Evaluation and Management"

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and

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U.S. Department of Transportation

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data reported herein. The contents do not necessarily reflect the official views in policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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16. Abstract This report applies the mathematics of fuzzy sets that was created in the companion Interim Report by Gunaratne, et al. (FHWA/IN/JHRP-84/18). The new scheme being suggested for pavement management is predicated on the presence of uncertainty at various stages in pavement management which requires that judgment be used in the process. The fuzzy sets mathematics can methodically combine subjective information and crisp measurement data. Fuzzy sets are used to represent the subjectivity in pavement serviceability ratings and distress surveys, and the variability in Roadmeter, Skid-Tester and Dynaflect readings. The ranking of pavements is formulated using fuzzy multi-attribute decision-making concepts using an expert knowledge base. To use the new scheme required the one-time development of the knowledge base. Any time thereafter, performance data can be applied to develop a crisp rank-ordering of pavements according to their maintenance urgency. This report presents details of the development of the knowledge base using responses from experts to appropriate questionnaires. Suggestions are also included for improvements in the pavement management program to take full advantage of the possibilities offered by this new scheme.					
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TABLE OF CONTENTS

	Page
LIST OF TABLES.....	vi
LIST OF FIGURES.....	x
LIST OF SYMBOLS AND ABBREVIATIONS.....	xiii
HIGHLIGHT SUMMARY.....	xv
INTRODUCTION.....	1
Knowledge base.....	2
Decision process.....	3
CHAPTER 1 : PAVEMENT EVALUATION 1: RIDEABILITY.....	5
Introduction.....	5
Pavement Serviceability Rating (PSR).....	6
Variability of the Roadmeter Reading.....	18
PSR-RR relationship and fuzzy PSR.....	20
Summary	30
CHAPTER 2 : PAVEMENT EVALUATION 2 : SKID, DEFLECTION AND DISTRESS.....	32
Skid-tester variability.....	32
Dynalect variability.....	35
Variability in Pavement Condition Rating (PCR).....	39
Summary.....	42
CHAPTER 3 : DATA BASE RELATED TO THE PAVEMENT SECTIONS TO BE RANKED.....	44
CHAPTER 4 : DECISION MAKING 1: INITIAL SCREENING OF PAVEMENT SECTIONS.....	64
Acceptable Serviceability Range.....	65
Nonacceptable Serviceability Range.....	68
Acceptable and Nonacceptable Friction Number.....	68

Screening of pavements.....	71
Summary.....	85
 CHAPTER 5 : DECISION MAKING 2: PRIORITY ASSIGNMENT.....	89
Attributes for immediate maintenance.....	89
Typical application for sections in categories 1 and 2.....	94
Attributes for future maintenance.....	96
Summary.....	107
 CHAPTER 6 : SUMMARY AND CONCLUSIONS.....	115
Summary.....	115
Conclusions.....	118
 CHAPTER 7 : RECOMMENDATIONS.....	120
 BIBLIOGRAPHY.....	122
 APPENDICES	
Appendix A : Questionnaires and responses.....	125
Appendix B : π curve.....	199
Appendix C : Fuzzy Pavement Condition Rating (PCR).....	201
Appendix D : Parametric studies for the RR and FN versus acceptability index relationship.....	206
Appendix E : Fuzzy PSI, FN, PCR for the data base.....	227
Appendix F : Computer programs.....	237

LIST OF TABLES

Table	Page
1.1 A Grouped Rating Panel	8
1.2 Weights for Grouping the Panel Raters	10
1.3 Weights for Subgrouping the Panel Raters	10
1.4 PSR vs. RR Data for 28 Asphalt Pavement Sections	12
1.5 PSR vs. RR Data for 20 Overlay Pavement Sections	13
1.6 PSR vs. RR Data for 21 JRCF Sections	14
1.7 PSR vs. RR data for 19 CRCP Sections	15
1.8 Ranges of Variation for the Roadmeter Reading	19
1.9 PSR-RR Matrix, Developed Using Data from 28 Asphalt Sections Rated by a Panel of Raters	25
1.10 Closer View of the PSR-RR Matrix, Developed Using Data from 28 Asphalt Sections Rated by a Panel of Raters	27
1.11 PSR-RR Matrix, Developed Using Higher Ranges of Variation for PSR and RR	28
1.12 PSR-RR Matrix, Developed Using Information from 233 Asphalt Sections	29
2.1 Variability of FN Due to Climatic Changes	34
2.2 Dynaflect Reading Variation	38
2.3 Range of Variation for PCR Values	41
3.1 Data Summary for Asphalt Pavement Sections	47
3.2 Data Summary for Overlay Pavement Sections	49
3.3 Data Summary for JRCF Sections	55

3.4	Data Summary for CRCP Sections	61
4.1	RR Screening Results for Asphalt Sections	77
4.2	RR Screening Results for Overlay Sections	78
4.3	RR Screening Results for JRCF Sections	79
4.4	RR Screening Results for CRCP Sections	80
4.5	FN Screening Results for Asphalt Sections	81
4.6	FN Screening Results for Overlay Sections	82
4.7	FN Screening Results for JRCF Sections	83
4.8	FN Screening Results for CRCP Sections	84
4.9	Primary Categorization of Pavements	86
4.10	Primary Categorization of Pavement Sections Included in the Data Base	87
5.1	Ranking of Asphalt Sections. Nonacceptable Roughness.....	97
5.2	Ranking of Overlay Sections. Nonacceptable Skid Resistance.....	97
5.3	Ranking of JRCF Sections. Nonacceptable Skid Resistance.....	98
5.4	Ranking of JRCF Sections. Nonacceptable Roughness.....	98
5.5	PSI Life and Friction Life for Overlay Pavement Sections	109
5.6	PSI Life and Friction Life for JRCF Sections	110
5.7	PSI Life and Friction Life for CRCP Sections	111
5.8	Ranking of Overlay Sections. Acceptable Roughness and Skid Resistance	112
5.9	Ranking of JRCF Sections. Acceptable Roughness and Skid Resistance	113
5.10	Ranking of CRCP Sections. Acceptable Roughness and Skid Resistance	114

Appendix Table

A1. List of a Rating Panel	132
A2. A Grouped Rating Panel	133
A3. Weights for the Opinion of Highway Users Who Could be Called to Serve on Rating Panels	134
A4. Weights for Grouping (1.0-2.0)	135
A5. Weights for Subgrouping	136
A6. ASI (Acceptable Serviceability Index)	141
A7. NASI (Nonacceptable Serviceability Index)	141
A8. Range of Variation for PSR	141
A9. Range of Variation for RR Due to Irrepeatability ...	142
A10. Gas Tank Level Effect on RR Range	142
A11. Air Temperature Effect on RR Range	142
A12. Driver Characteristics Effect on RR Range	142
A13. Acceptable Serviceability Range	143
A14. Nonacceptable Serviceability Range	144
A15. Acceptable Friction Number	150
A16. Acceptable Friction Number Range	151
A17. Nonacceptable Friction Number	152
A18. Nonacceptable Friction Number Range	153
A19. Range of Variation Due to Climatic Changes	154
A20. Range of Variation Due to Vehicle Speed Changes	154
A21. Range of Variation for Dynaflect Reading at the Same Location on Repeated Trials, Assuming No Climatic Changes	160
A22. "Edge Deflection/Center Deflection" Values	160
A23. Tolerance to be attached to the Above Factors	161
A24. Ratio of Spring Deflections/Fall Deflections	161

A25. Tolerance to be Attached to the Above Factors	161
A26. Acceptable PCR	167
A27. Range of Variation for PCR	168
A28. (ADT , FN , PCR)	177
A29. (FN , ADT)	179
A30. (ADT , PSI , PCR)	190
A31. (Def. , PCR , ADT)	192
A32. (FN life, PSI life) in years	197

LIST OF FIGURES

Figure	Page
1.1 Typical Fuzzy PSR Obtained Using the Opinion of a Single Rater	16
1.2 Typical Fuzzy PSR Obtained Using the Combined Opinion of a Panel of Raters	16
1.3 Typical Fuzzy Roadmeter Reading	21
1.4 Representation of Strength of the Strongest Chain	23
2.1 Typical Fuzzy Friction Number	36
2.2 Typical Fuzzy Pavement Condition Rating	43
4.1 Acceptable Serviceability Range for Primary Pavements	66
4.2 Acceptable Serviceability Range for Secondary Pavements	67
4.3 Acceptable and Nonacceptable Serviceability Ranges for Primary Pavements	69
4.4 Nonacceptable Serviceability Range for Secondary Pavements	70
4.5 Acceptable Friction Number Range for Flexible and Concrete Pavements	72
4.6 Nonacceptable Friction Number Range for Flexible Pavements	73
4.7 Nonacceptable Friction Number Range for Concrete Pavements	74
5.1 Typical Fuzzy PSI Life	104
5.2 Typical Fuzzy FN Life	106

Appendix
Figure

B1. Typical π Curve	200
C1. Fuzzy Distress Rating for Distress 1	203
C2. Fuzzy Distress Rating for Distress 2	204
C3. Fuzzy PCR Obtained Taking Into Account Distress 1 and 2	205
D1. Range of Variation Effect on Acceptability Index vs. RR Relationship	208
D2. Variable Number of Sections Effect on Acceptability vs. RR Relationship	209
D3. Relationship Between Central PSI and RR	210
D4. Relationship Between Width of Fuzzy PSI and Central PSI	211
D5. Relationship Between Central PSI and RR	212
D6. Relationship Between Width of Fuzzy PSI and Central PSI	213
D7. Relationship Between Central PSI and RR	214
D8. Relationship Between Width of Fuzzy PSI and Central PSI	215
D9. Relationship Between Central PSI and RR	216
D10. Relationship Between Width of Fuzzy PSI and Central PSI	217
D11. Acceptability and Nonacceptability Index vs. RR for Asphalt Pavements Using the PSR-RR Matrix	218
D12. Acceptability and Nonacceptability Index vs. RR for Asphalt Pavements. The Proposed Method to Develop Fuzzy PSI was Used	219
D13. Acceptability and Nonacceptability Index vs. RR for Overlay Pavements Using the PSR-RR Matrix	220

D14. Acceptability and Nonacceptability Index vs. RR for Overlay Pavements. The Proposed Method to Develop Fuzzy PSI was Used	221
D15. Acceptability and Nonacceptability Index vs. RR for JRC Pavements Using the PSR-RR Matrix	222
D16. Acceptability and Nonacceptability Index vs. RR for JRC Pavements. The Proposed Method to Develop Fuzzy PSI was Used	223
D17. Acceptability and Nonacceptability Index vs. RR for CRC Pavements Using the PSR-RR Matrix	224
D18. Acceptability and Nonacceptability Index vs. RR for CRC Pavements. The Proposed Method to Develop Fuzzy PSI was Used	225
D19. Acceptability and Nonacceptability Index vs. FN for Flexible and Rigid Pavements	226

LIST OF SYMBOLS AND ABBREVIATIONS

AASHO	- American Association of State Highway Officials
ADT	- Average Daily Traffic
ANOVA	- Analysis of variance
ASI	- Acceptable serviceability index
ASR	- Acceptable serviceability range
ASTM	- American Standards of Testing Materials
CRC	- Continuously reinforced concrete
D_1	- Thickness of layer 1
EAL_0	- Initial equivalent axle load
ESAL	- Equivalent single axle load
FN	- Friction number
IDOH	- Indiana Department of Highways
JRC	- Jointly reinforced concrete
K	- Kernel of fuzzification
max	- Maximum
min	- Minimum
PCA	- Portland Cement Association
PCR	- Pavement condition rating
PMS	- Pavement Management System
PSI	- Pavement serviceability index
PSR	- Pavement serviceability rating

P_t	- PSI at time t
RR	- Roadmeter reading
SN	- Structural number
SPI	- Index used for friction measured in spring
SUI	- Index used for friction measured in summer
Sup	- Supremum
T	- Design thickness of a pavement
TRB	- Transportation Research Board
w_i	- Weight of i
$w_{t_{18}}$	- Equivalent 18 kilo-pound axle load at time t
α	- Concentration index
μ	- Membership value
μ_A	- Acceptability index
μ_N	- Unacceptability index
θ	- Distress rating
X	- Cartesian product of two sets

INTRODUCTION

Many pavement characteristics that affect performance are not precisely defined, and experience and engineering judgement are often used to supplement scientific knowledge in evaluating pavement performance. A number of recent studies have shown that fuzzy sets mathematics can be an appropriate tool to include subjective information in decision making. This feature of the theory of fuzzy sets motivated the study of its potential use in pavement evaluation and management.

This report follows the framework proposed by Gunaratne (1984) for the use of fuzzy sets in pavement evaluation and management. It demonstrates how the knowledge base required by the decision making techniques can be acquired from the responses given by highway experts to selected questionnaires. Once the knowledge base is available, it can be used to categorize and prioritize any number of pavement sections for which performance and traffic data are available.

Each chapter in this report has two goals: (1) To show how the knowledge base can be acquired, and (2) To illustrate the use of this knowledge base on a typical data set. The questionnaires which can be used to generate the knowledge base are presented and the limitations of the answers obtained in this study are

Knowledge base

The knowledge base consists of the following elements:

- 1) Ranges of variations of Pavement Serviceability Rating (PSR), Roadmeter Reading (RR), Friction Number (FN) and Pavement Condition Rating (PCR).
- 2) Ratings of a panel of users who evaluate the rideability of selected pavement sections. Allowance is made for the subjectiveness inherent to the ratings and the variation of perceptiveness among the raters.
- 3) A relationship between Pavement Serviceability Rating and Roadmeter Reading.
- 4) Acceptable and nonacceptable levels for Pavement Serviceability Index and Friction Number.
- 5) Utility values provided by experts for selected attributes that affect the ranking of the pavements. The attributes to be included can be chosen according to experts' information and available data.

Decision process

The decision process consists of several steps. The first one is to screen the pavements with respect to roughness. The PSR-RR knowledge base is used to obtain a Pavement Serviceability Index. The PSI of each pavement section is compared to the acceptable and nonacceptable levels provided by the experts. As a result of this comparison, the pavement sections are categorized according to their roughness. Similarly, the friction number of each section is compared to acceptable and nonacceptable friction levels resulting in a screening of the pavements with respect to their skid resistance.

Three categories are formed according to the results of the screening operation:

- Sections with nonacceptable skid resistance.
- Sections with nonacceptable roughness.
- Sections with acceptable roughness and skid resistance.

A separate prioritization is performed for pavements included in each of the three categories. Different attributes, which depend on the category the section belongs to, affect this prioritization. In this study, Annual Daily Traffic (ADT), FN and PCR are included as attributes in the first category. ADT, PSI and PCR are the attributes considered for ranking pavements in the second category, and Friction and PSI Lives are the attributes for the third category. Experts are asked to provide

utility values for selected combinations of these attributes. Utility functions can then be developed from their answers for each category of pavements.

The relative priorities for maintenance of pavement sections are obtained using the utility functions. A unique criterion (Gunaratne, 1984) is created to provide a single-valued ranking of the pavement sections. The input to this ranking operation consists of the performance and traffic data necessary for each category of pavements. A typical example is provided for the ranking of a number of pavement sections for which performance and traffic data were supplied by the Indiana Department of Highways (IDOH).

It should be noted that once the knowledge base is established, the performance and traffic parameters for the pavements to be ranked, i.e. RR, FN, PCR, ADT etc. are the only data required in the analysis. With this data, the initial screening and final ranking of the pavements are performed using the knowledge base stored in the computer and the programs written to perform these operations.

In the future, improvement of the decision scheme is possible by selecting different or additional decision attributes. The knowledge base can also be updated periodically to accommodate changes in vehicle design or other such characteristics. This can be accomplished by sending new questionnaires to the experts and having a number of road users evaluate the rideability of pavement sections.

CHAPTER 1
PAVEMENT EVALUATION 1 : RIDEABILITY

Introduction

In many states, the initial screening of road sections to determine maintenance needs is done using roughness as the basic criterion. Roughness is considered to be the pavement characteristic that has the most important influence on pavement rideability.

Roughness measurements in Indiana are conducted using the PCA (Portland Cement Association) roadmeter. These measurements are converted to a Pavement Serviceability Index (PSI) using regression equations, developed by correlating Roadmeter Readings (RR) and Pavement Serviceability Ratings (PSR) for a sample of road sections (Mohan, 1978).

Gunaratne (1984) proposed to improve the existing technique by correlating RR and PSR using simple concepts from the theory of fuzzy sets. This chapter shows how the information provided by highway experts can be used to apply the procedure proposed by Gunaratne.

Pavement Serviceability Rating (PSR)

Pavement serviceability ratings come from a panel of road users of different backgrounds and ages who rate selected pavement sections on a scale of 0.0 to 5.0, according to their evaluation of the sections' rideability. In the conventional approach individual ratings are treated as random variables and the reported PSR of a particular road section is the average of the individual ratings.

In this work, it is desired to make allowance for two important characteristics of the rating procedure which are not considered by the conventional approach. First, the rating involves human judgement and thus sizeable subjectivity and uncertainty. Second, the significance of a given rating is a function of the perceptiveness of the rater in assessing the source of ride roughness. Hence, distinction should be made between the ratings of people with different professional backgrounds.

Fuzzy logic can be used to develop a PSR which reflects human uncertainty and the relative significance (or perceptiveness) of the judgements of various panel members. The resulting PSR contains more information than the conventional one, because it shows the region of support as well as the degree of support for each possible value in the range 0.0 to 5.0. Furthermore, it incorporates each individual's perceptiveness of pavement performance while carrying all judgements through to the final stage of analysis without discarding any of them.

The most important concept in the development of the new PSR is to separate the rating panel into groups of raters with similar backgrounds, to account for differences in perceptiveness. Furthermore, to avoid any differences within a group such as experience, age, etc., each group is subdivided into a sufficient number of subgroups. Questionnaire No.1 was prepared to determine from highway experts whether this approach was desirable. The characteristics of a typical rating panel previously used by IDOH (Partridge, 1982) were submitted to the experts. A number of groups and subgroups were identified based on profession and age characteristics which may introduce differences in perceptiveness (Table 1.1). Note that this is only a typical example and other panels and groups could be used in future implementation. The experts were also asked to provide weights for the relative importance of each group and subgroup.

Responses were received from fifteen experts from the Federal Highway Administration and the Indiana Department of Highways. The following results were obtained:

1. Nine out of fifteen experts agreed with grouping of the panel and suggested weighting factors for each group. According to the responses, higher importance factors were suggested for raters with more technical skills.
2. Eight out of fifteen experts agreed with subgrouping according to experience and other factors. The other experts thought that a subgrouping is not necessary.

Table 1.1. A Grouped Rating Panel.

A Group			B Group		C Group	
	Profession	Age	Profession	Age	Profession	Age
Major	Research Eng.	50-59	Engineering Asst.	50-59	Lab. Technician	20-29
	Research Eng.	50-59	Eng. Asst. Super.	30-39	Mechanic	30-39
					Electronics Technician	40-49
Minor	Research Eng.	30-39	Eng. Assistant	30-39	Training Off.	40-49
	Research Eng.	20-29	Eng. Assistant	20-29	Secretary	30-39
	Research Eng.	20-29	Eng. Assistant	20-29		
			Eng. Assistant	20-29		

Using the grouping of raters in Table 1.1, responses from questionnaire No.1 suggested the average weighting factors given in Table 1.2 and Table 1.3. The weights obtained for the groups indicate that the profession of the raters is considered an important factor affecting their perceptiveness. More importance is given to the opinion of research engineers (group A) when compared to engineering assistants (group B) or technicians (group C). These weights obtained for the subgroups suggest that higher relative weight should be given to the opinion of more experienced raters, considering their age and background. The weights (w_i 's) provided for the subgroups were normalized so that their sum adds to 1.0, as required by the proposed techniques (Gunaratne, 1984).

A second questionnaire was submitted to experts to establish the range, or spread, inherent in a rater's response. The range represents the vagueness (i.e. uncertainty) attached to the single value given by the rater. This range can then be incorporated in a mathematical framework (Gunaratne, 1984) to make allowance for this vagueness. Note that, although information with regard to this range was sought from highway experts, it may be possible in the future to ask panel members to provide this information on their rating forms.

Responses from seven experts were obtained to questionnaire No.2. According to these answers, all of the experts were in agreement with the idea that an individual opinion for the PSR is better represented by a range rather than by a discrete number.

Table 1.2. Weights for Grouping the Panel Raters.

<u>Group</u>	<u>Weight (0.0-2.0)</u>
A	$\alpha = 1.64$
B	$\beta = 1.19$
C	$\gamma = 0.77$

Table 1.3. Weights for Subgrouping the Panel Raters.

<u>Minor (w_1)</u>	<u>Major (w_2)</u>
0.57	0.82
Normalized 0.41	0.59

$$\sum_i w_i = 0.41 + 0.59 = 1.00$$

An average range of variation of ± 0.25 was suggested by the experts' responses.

Data provided by the IDOH Research and Training Center (Partridge, 1982) includes the PSR values provided by a panel of raters. Information was available for four types of pavements: Flexible pavements (asphalts), overlays, Continuously Reinforced Concrete Pavements (CRCP) and Jointed Reinforced Concrete Pavements (JRCP). One mile test sections for each pavement type were randomly chosen among roads within an 80 mile radius of Lafayette. These test sections were arranged in five loops. Each rater was instructed not to drive more than one loop on a single day and the loop order was random and specific to each rater. The rating team was composed of sixteen persons of both sexes (Table 1.1) who were instructed to rate each test section on a scale of 0.0 to 5.0. Roadmeters operated by the Research and Training Center were used to measure the roughness for the test sections. The PSR provided by the panel of raters and the RR for the rated sections are included in Tables 1.4 to 1.7.

The PSR values that each member in the panel provided for a given pavement section, were converted to fuzzy sets that were centered around the PSR value itself. The degree of belief is 1.0 for the central PSR value and is decreasing for PSR values above and below the central value, π curves (Figure 1.1) were used in calculating the membership of all the PSR values in the range suggested by the experts. (The mathematical representation of π curves is given in Appendix B). All these membership functions

Table 1.4. PSR vs. RR Data for 28 Asphalt Pavement Sections.

Raters	Am	Cm	Am	AM	Am	CM	Cm	AM	Bm	CM	Bm	Bm	Bm	Roadmeter
loop 1	2.0	3.2	2.9	3.4	3.6	3.0	2.8	2.1	2.7	3.1	3.5	2.9	3.2	2.5
	2.2	3.7	3.1	3.0	3.7	3.0	4.0	2.7	3.1	2.7	3.1	3.6	3.5	3.2
	3.5	3.6	3.3	3.7	3.8	3.9	5.0	3.4	3.4	3.3	3.9	4.5	4.0	3.5
	1.5	1.5	1.5	2.8	3.8	0.8	2.6	1.5	2.2	3.0	3.4	2.7	1.0	1.5
	2.7	2.9	2.8	3.0	3.7	2.6	3.0	3.5	3.5	2.9	4.1	3.7	3.1	2.8
loop 2	2.9	4.2	2.9	3.5	3.5	3.7	3.0	3.8	3.5	3.2	4.2	3.7	3.3	4.0
	3.0	4.0	2.9	3.7	3.5	3.7	3.0	3.9	3.5	3.0	3.9	3.7	3.2	2.5
	3.5	4.3	3.9	4.2	4.7	4.2	5.0	4.1	4.1	3.5	4.7	4.3	4.6	3.5
	3.2	4.2	3.7	4.2	4.6	4.6	5.0	3.7	4.1	3.5	4.0	4.6	3.3	4.6
	3.0	4.0	4.0	4.3	4.6	4.5	5.0	3.9	4.3	3.5	3.7	4.5	4.0	4.0
loop 3	3.0	4.2	3.9	4.4	4.4	4.0	5.0	4.0	4.1	3.0	3.8	4.4	4.3	4.2
	2.0	4.1	3.5	3.8	4.4	3.5	3.0	3.2	3.8	2.5	2.8	3.9	3.5	4.0
	1.7	3.7	3.5	3.6	4.0	3.0	3.0	3.6	2.3	3.0	3.7	3.2	3.1	4.0
	1.5	2.5	3.0	2.8	3.5	2.5	3.0	2.2	3.0	2.8	2.7	3.5	3.3	2.8
	1.0	3.3	2.1	2.4	2.6	1.0	2.2	1.3	2.0	1.8	2.0	1.8	1.0	2.9
loop 4	0.9	2.6	3.2	3.3	3.0	2.6	3.0	1.8	2.7	2.6	2.0	2.5	2.9	2.8
	1.0	2.6	2.5	3.0	2.8	3.0	1.7	2.7	2.5	2.2	3.3	3.0	2.5	1.5
	0.5	2.0	2.2	1.1	2.5	1.5	2.0	1.8	2.0	1.4	1.8	3.0	2.7	1.2
	3.3	3.2	2.7	3.5	2.9	2.5	2.4	2.0	2.7	2.6	2.8	3.0	2.5	783
	3.0	2.5	3.0	3.8	4.4	4.1	4.0	3.1	4.5	3.5	3.7	3.5	3.7	3.4
loop 5	4.5	4.4	4.7	4.8	4.5	4.0	3.8	4.4	3.7	4.1	4.0	4.3	4.5	3.5
	1.5	2.9	2.5	2.5	3.0	1.4	2.0	2.1	1.9	2.6	2.8	3.1	2.7	1.6
	0.7	2.8	2.1	2.5	2.4	1.5	2.0	1.5	1.7	2.2	1.8	2.8	2.5	1.6
	2.6	3.5	2.5	3.5	3.2	3.5	3.0	1.9	3.5	3.4	3.9	4.4	3.8	3.3
	2.3	3.3	2.7	2.9	3.7	3.2	2.5	2.9	3.3	2.7	2.3	3.6	3.1	2.9
loop 6	3.1	3.5	3.0	3.4	3.9	2.4	3.0	2.5	3.8	3.5	3.2	4.0	3.8	3.2
	1.4	3.4	2.9	3.2	3.6	3.8	4.0	2.7	3.5	2.8	2.3	3.6	2.8	2.1
	2.6	3.5	2.5	3.5	3.2	3.5	3.0	1.9	3.5	3.4	3.9	4.4	3.8	3.3
	2.3	3.3	2.7	2.9	3.7	3.2	2.5	2.9	3.3	2.7	2.3	3.6	3.1	2.9
	3.1	3.5	3.0	3.4	3.9	2.4	3.0	2.5	3.8	3.5	3.2	4.0	3.8	3.2

m: minor
M: major
A, B, C grouping
categories

Table 1.5. PSR vs. RR Data for 20 Overlay Pavement Sections.

Raters	Am	Cm	Am	Am	BM	CM	AM	Rm	Rm	Bm	BM	Roadmeter
loop 1	2.1	2.5	2.9	3.5	2.6	2.5	2.9	3.5	2.5	2.2	3.0	1.8 3.0
loop 2	2.2	3.1	2.9	3.2	4.2	3.0	2.3	2.3	3.1	2.7	2.9	3.8 2.5
	1.7	2.7	3.1	3.7	3.7	2.2	2.1	3.0	2.7	3.0	1.5	1744
	2.0	3.5	2.9	3.5	3.7	2.8	2.7	2.1	3.0	2.7	2.0	1.5 728
loop 3	3.7	3.9	3.8	4.5	4.2	3.8	3.9	3.3	4.2	3.1	4.3	3.6 4.0
	3.4	3.7	3.5	4.3	4.0	3.7	3.8	3.3	4.2	3.2	4.3	3.6 4.0
	3.5	3.7	3.2	4.0	3.7	3.5	3.4	4.0	3.3	4.3	4.1	4.0 430
	3.2	3.9	3.2	4.3	4.0	3.7	4.2	3.5	3.9	3.0	4.3	4.4 6.0 350
loop 4	4.0	4.1	2.9	4.5	4.5	3.8	2.8	3.4	3.7	3.3	3.9	3.7 4.0 435
	3.5	4.4	4.2	4.9	4.6	3.8	4.1	3.4	4.6	3.9	4.6	4.3 4.0 127
	3.5	4.3	4.1	4.8	4.6	3.7	4.0	3.5	4.6	3.9	4.5	4.4 4.0 122
	3.3	3.7	4.1	4.6	4.5	3.8	3.8	3.8	4.1	3.7	4.5	4.1 3.5 518
	3.8	4.4	3.9	4.9	4.2	3.9	3.6	3.5	4.6	3.9	4.7	4.3 4.0 119
loop 5	2.7	3.9	2.7	3.2	4.4	3.6	3.8	2.7	3.7	3.0	3.7	4.4 3.0 788
	2.5	3.9	2.8	3.0	4.4	3.6	3.7	2.8	3.5	3.0	3.5	4.1 3.0 549
	2.6	3.9	3.0	3.0	4.4	3.6	3.7	2.9	4.0	3.0	3.5	3.6 3.0 268
	2.8	2.9	3.0	3.0	3.9	3.5	3.5	3.0	3.8	2.8	3.6	3.5 3.0 389
	0.8	2.2	2.3	2.4	3.0	2.0	2.1	1.3	2.8	2.2	1.4	1.9 2.0 1307
	0.6	2.4	2.6	2.1	2.4	2.0	1.6	1.3	1.9	1.8	1.6	1.1 2.0 1108
	0.5	2.4	2.5	2.0		1.9	1.5	1.4	1.4	1.2	0.9	2.0 1019

m:minor
M:major

A, B, C grouping
categories

Table 1.7. PSR vs. RR Data for 19 CRCP Sections.

Raters	Am	Am	Am	CM	AM	Bm	Bm	Roadmeter
Loop 1	3.1	2.4	3.7	2.5	3.3	2.3	4.0	1718
	2.9	2.6	3.6	2.3	3.3	2.2	3.6	1016
	3.0	2.6	3.8	3.4	3.5	2.5	3.8	1056
	3.5	3.2	3.7	2.5	3.5	2.6	3.7	787
Loop 2	2.6	3.5	3.8	3.0	4.2	3.9	4.0	601
	3.5	3.7	3.8	3.5	3.5	4.1	4.1	475
	3.6	3.0	3.9	2.9	3.7	3.7	3.9	721
	3.5	3.5	3.8	2.7	3.7	3.6	4.2	599
Loop 3	3.7	3.5	3.8	3.1	3.8	3.9	4.8	573
	3.7	3.8	3.8	3.5	3.8	4.1	4.5	598
	3.1	1.8	3.8	1.8	3.5	2.8	1.5	1325
	4.4	3.2	3.4	3.5	2.3	5.8	4.4	1048
Loop 5	1.9	2.5		1.8	2.3	2.3	1.7	1769
	3.1	2.9	3.6	2.5	2.8	2.3	2.9	1145
	3.2	2.3	3.4	2.8	2.8	2.6	2.5	998
	2.8	2.5	3.5	2.2	3.0	2.4	3.3	1120
Loop 5	2.9	2.4	3.3	2.2	3.0	2.2	2.2	1728
	3.3	2.7	3.5	4.0	2.9	2.6	4.0	1062
	3.1	2.8	3.4	3.2	3.0	2.5	3.7	1184

m: minor
M: major

A, B, C grouping
categories

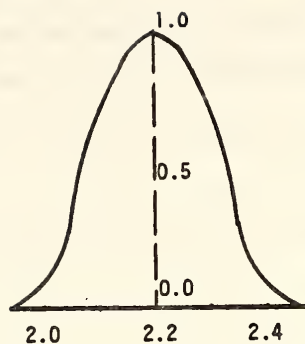


Figure 1.1. Typical Fuzzy PSR Obtained Using the Opinion of a Single Rater.

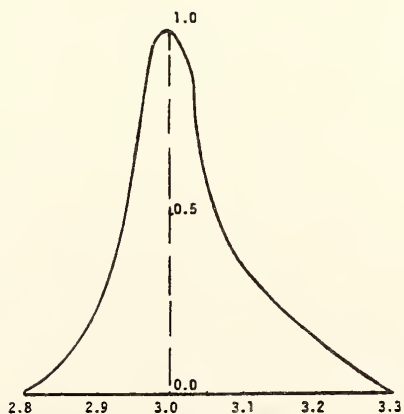


Figure 1.2. Typical Fuzzy PSR Obtained Using the Combined Opinion of a Panel of Raters.

represent opinions that can be combined to obtain the fuzzy PSR of each pavement section. The techniques to perform this combination were described by Gunaratne (1984) and are reviewed below.

An opinion shows the degree of belief that an individual has in certain PSR values. Opinions of all raters in a given subgroup are weighted equally. A combined opinion for that particular subgroup is obtained considering all of the suggested values without discarding any of them. This is accomplished by the Union operation, because the Union operation provides the maximum degree of belief when the opinions of two raters are compared for a given PSR value. The opinions of subgroups are then multiplied by their respective relative weights (w_1, w_2, \dots). They are also combined by the Union operation so that all subgroup opinions are included with none being discarded. Furthermore, to insure that the importance factor for each group is taken into account, the group opinions are raised to the power of the corresponding weighting factor. If the weighting factor (Table 1.2) is above 1.0, it means that the particular group under consideration is more significant than others. Next, the judgment of each group of raters is carried to the final PSR by multiplying group opinions by each other.

Using this method, the fuzzy PSR was obtained for each of the pavement sections rated by the panel of raters. As a typical example, the fuzzy PSR for the second of the asphalt sections in loop 1 (Table 1.4) is shown on Figure 1.2. For that particular section, the degree of belief (membership) is 1.0 for a PSR of

3.0 and is skewed on the right side (range between between 2.8 and 3.3). All these fuzzy pavement serviceability ratings, obtained from the data set provided by IDOH (1982), will be used in a subsequent section to generate the PSR-RR relationship.

Variability of the Roadmeter Reading

The Roadmeter Reading is obtained with a mechanism that records the cumulative vertical movement along the pavement profile. This measurement depends on the exact path traced by the vehicle (repeated measurements show scatter) and on other parameters such as gas tank level, air temperature and driver characteristics.

Questionnaire No.2 included questions to assess the variability in roadmeter measurements. The responses to this questionnaire showed that the average range of variation of the roadmeter measurements due to the different paths traced by the vehicle is expected to be $\pm 9.0\%$ of the central value. Three out of seven experts indicated that they had insufficient experience to answer the question related to the range of variation of RR with air temperature, gas tank level and driver characteristics. The responses that were received from the other four experts were averaged and the results are given in Table 1.8. The fact that three out of the seven experts contacted did not provide answers to the questions related to the variations of RR with these factors makes questionable the validity of the ranges given in Table 1.8. Nevertheless, since no other information was available to

Table 1.8. Ranges of Variation for the Roadmeter Reading.

	<u>Range of variation</u>
a) Irrepeatability of the path traced	$\pm 9.00\%$
b) Gas tank level effect	$\pm 0.38\%$
c) Air temperature effect	$\pm 1.06\%$
d) Driver characteristics	$\pm 1.63\%$

In each of the above cases the other factors are assumed to have the standard condition values. These are:

Gas Tank Level : 1/2 Full

Air Temperature: 60° F

Driver Type : Steady

the present study, they were used as provided. It is recommended that a larger number of experts be contacted to obtain information on these variations for future implementation.

The fuzzy RR was obtained (for each of the pavement sections ranked by the panel of raters) using the measured RR as a central value and the provided ranges of variation due to different factors affecting the RR (Table 1.8). As a typical example, the fuzzy RR for the second of the asphalt sections rated by the rating panel in loop 1 (Table 1.4) is shown on Figure 1.3.

PSR-RR relationship and fuzzy PSI

At the present time, the Pavement Serviceability Rating and the Roadmeter Reading are treated as crisp number and random variable respectively, and they are correlated by regression analysis (Mohan, 1978). Using the new approach, both PSR and RR are mathematically represented by fuzzy sets which make allowance for the vagueness in these parameters as evaluated from the answers to questionnaires 1 and 2. Analytical techniques ("fuzzy relationships") are available to develop a relationship between PSR and RR. The mathematical details of these techniques have been presented by Gunaratne (1984) and will not be repeated here. Emphasis will be given to the data necessary for implementation of the techniques and to the physical meaning of the PSR-RR relationship.

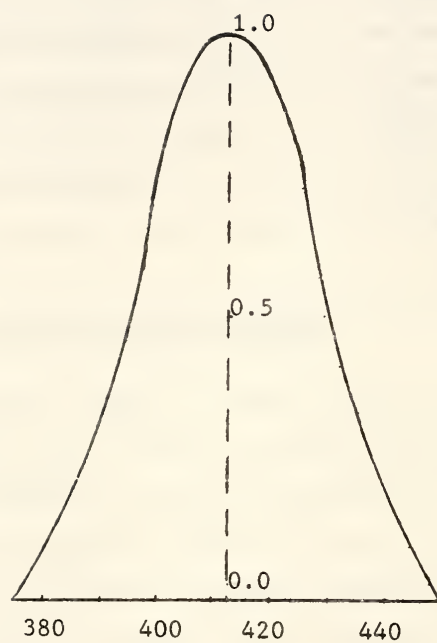


Figure 1.3. Typical Fuzzy Roadmeter Reading.

The fuzzy PSR and RR for each of the pavement sections rated by the panel of raters were developed as explained in the previous section. For a given pavement section, each PSR value is associated with a membership value. This membership represents the degree of belief attached to that particular PSR value. Similarly, a degree of belief is attached to each RR value. Then, a cartesian product is used to develop the relationship between PSR and RR. The membership (degree of belief) of the PSR-RR pair is obtained by considering the strength of the connection between those two numbers. The strength of this connection is governed by the weakest link between the given PSR and RR values, i.e. by the lowest degree of belief in either the PSR or RR values. In simple terms, it means that one can not "believe" more in the pair than one does believe in either of the two values composing the pair. Hence, the membership of the given PSR-RR pair is the smallest of the two memberships of the PSR and RR values. Such relationships can be formed for all the sample sections covering wide ranges of PSR and RR. For a given PSR-RR pair, different membership values result from the relations formed for different sections. In forming the resultant membership for that particular pair, membership values from all pavement sections are considered: the maximum of these values is taken as the representative membership of this pair for the highway network.

A simple analog can be made between this procedure and the strength of a number of chains (Figure 1.4) when one wants to select the strongest chain to move a load. The strength of a

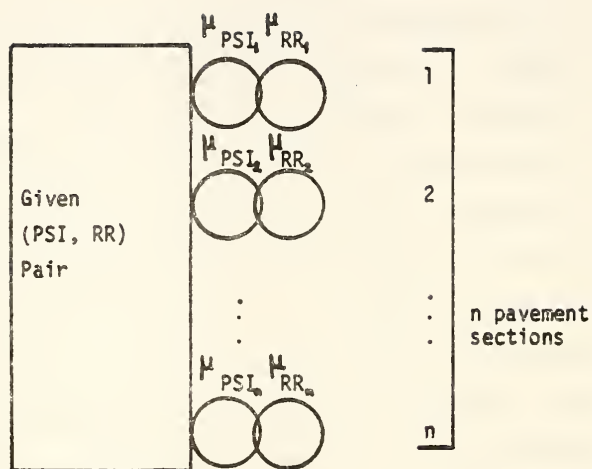


Figure 1.4. Representation of Strength of the Strongest Chain.

given chain is governed by the strength of the weakest link and, thus, each chain can not be stronger than its weakest link. Similarly, a rater can not believe in a given PSR-RR pair more than he or she believes in either of its components (i.e., minimum membership value). Then, the chain with the maximum strength is selected to move the load (i.e., the membership for a given PSR-RR pair is represented by the strongest degree of belief among the values obtained for that particular pair from all the pavement sections).

The computer program "road.f" was developed to perform all these operations. The program fuzzifies (i.e. make allowance for vagueness or uncertainty in data) the PSR and RR values for the rated pavement sections. It also forms the PSR-RR relationship using the above procedure. This relationship represents the knowledge base that can then be used to evaluate the Pavement Serviceability Index (PSI) of any pavement section for which a RR value has been measured. The program also performs this latter operation.

Although this procedure is conceptually simple, problems may be encountered during its implementation when data are lacking. This was the case with the available data. A typical PSR-RR matrix (relationship) developed for asphalt sections is shown on Table 1.9. For example, if the RR-PSR pair (175, 0.5) is considered, a membership value of 0.0 is obtained. This means that these two values are not related to each other. This is expected because it is highly improbable that a rater would give a very

low rating (0.5) to a pavement having a small RR (175). On the contrary, examining Table 1.10, which is a more detailed view of part of the matrix in Table 1.9, the membership value of 0.0 for the pair (900,3.2) can only be explained by lack of data in that particular region of PSR-RR pairs. Such PSR and RR values both indicate that the pavement section is in relatively good condition with respect to roughness and, hence, one would expect a strong connection between the two (high degree of belief associated with this particular pair). Similar remarks can be made for a number of RR-PSR pairs in Table 1.10.

Several ways of dealing with the lack of data were examined during this study. Two techniques appear to be effective:

a) The ranges of variation of the PSR and RR were increased from ± 0.25 and $\pm 9.0\%$ to ± 0.4 and $\pm 30.0\%$, respectively. Gas tank level, air temperature and driver characteristics effects were not considered. Using these ranges, most of the empty sections of the PSR-RR matrix were filled (Table 1.11).

b) The second alternative to solve the problem was to generate more data artificially. For this purpose, PSR-RR pairs based on correlations developed by the IDOH were used. 200 to 300 pairs were selected for each pavement type (IDOH, Summary of 1983 Pavement Roughness). This data was used to complete the PSR-RR matrix that had been originally obtained with 20 to 30 sections rated by the panel of raters. The resultant matrix showed considerable improvement (Table 1.12) with respect to the

Table 1.10. Closer View of the PSR-RR Matrix, Developed Using Data from 28 Asphalt Sections Rated by a Panel of Raters.

	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
875	0.00	0.	0.	0.	0.09	0.09	0.00	0.00	0.09	0.00	0.37
900	0.	0.	0.	0.	0.49	0.45	0.	0.	0.49	0.	0.63
925	0.	0.	0.	0.	0.91	0.45	0.	0.	0.62	0.	0.63
950	0.	0.	0.	0.	0.99	0.45	0.01	0.	0.62	0.01	0.63
975	0.	0.	0.	0.	0.71	0.45	0.12	0.	0.62	0.12	0.37
1000	0.	0.	0.	0.	0.27	0.27	0.16	0.	0.27	0.40	0.49
1025	0.	0.	0.	0.	0.02	0.02	0.16	0.	0.02	0.40	0.88
1050	0.	0.	0.01	0.01	0.01	0.01	0.16	0.	0.	0.40	1.00
1075	0.	0.	0.15	0.15	0.15	0.15	0.16	0.	0.	0.40	0.85
1100	0.	0.	0.45	0.49	0.39	0.49	0.21	0.	0.	0.40	0.43
1125	0.	0.	0.45	0.85	0.39	0.85	0.21	0.	0.	0.18	0.12
1150	0.	0.	0.45	1.00	0.39	0.86	0.21	0.	0.	0.18	0.00
1175	0.	0.01	0.45	0.91	0.39	0.86	0.21	0.	0.	0.18	0.
1200	0.	0.12	0.45	0.61	0.39	0.61	0.21	0.	0.	0.18	0.
1225	0.	0.37	0.32	0.32	0.32	0.32	0.32	0.	0.	0.18	0.
1250	0.	0.71	0.54	0.64	0.66	0.66	0.63	0.	0.	0.03	0.
1275	0.	0.94	0.54	0.64	0.84	0.91	0.63	0.	0.	0.00	0.
1300	0.	1.00	0.54	0.64	0.84	1.00	0.63	0.	0.	0.	0.
1325	0.	0.85	0.54	0.64	0.84	0.88	0.63	0.	0.	0.	0.
1350	0.	0.60	0.54	0.61	0.61	0.61	0.61	0.	0.	0.	0.
1375	0.00	0.27	0.27	0.27	0.43	0.43	0.27	0.	0.	0.	0.

Table 1.11. PSR-RR Matrix, Developed Using Higher Ranges of Variation for PSR and RR.

	0.5	0.9	1.3	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.5
25	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
175	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
325	0.	0.	0.	0.	0.	0.	0.79	0.19	0.57	0.85	0.66
475	0.	0.	0.	0.	0.	0.	0.47	0.14	0.98	0.47	0.15
625	0.	0.	0.	0.	0.	0.19	0.19	0.15	0.54	0.01	0.
775	0.	0.	0.	0.	0.16	1.00	0.34	0.44	0.94	0.01	0.
925	0.	0.	0.02	0.02	0.16	0.63	0.99	0.85	0.60	0.01	0.
1075	0.	0.	0.17	0.10	0.41	0.40	0.80	0.60	0.37	0.	0.
1225	0.	0.	0.17	0.32	0.41	0.51	0.94	0.26	0.37	0.	0.
1375	0.	0.02	0.17	0.32	0.41	0.51	0.91	0.11	0.37	0.	0.
1525	0.	0.02	0.26	0.32	0.39	0.49	0.85	0.03	0.34	0.	0.
1675	0.	0.02	0.26	0.32	0.34	0.49	0.82	0.00	0.00	0.	0.
1825	0.	0.02	0.26	0.09	0.09	0.49	0.60	0.00	0.	0.	0.
1975	0.	0.02	0.26	0.34	0.34	0.23	0.50	0.00	0.	0.	0.
2125	0.	0.02	0.26	0.34	0.37	0.23	0.50	0.	0.	0.	0.
2275	0.	0.12	0.12	0.34	0.37	0.23	0.12	0.	0.	0.	0.
2425	0.	0.34	0.03	0.34	0.37	0.23	0.	0.	0.	0.	0.
2575	0.	0.62	0.03	0.34	0.37	0.23	0.	0.	0.	0.	0.
2725	0.	0.62	0.03	0.34	0.37	0.23	0.	0.	0.	0.	0.
2875	0.	0.62	0.03	0.19	0.19	0.19	0.	0.	0.	0.	0.

original one which is shown in Table 1.9.

The second method was chosen in this report to avoid modifying the ranges suggested by the experts. The PSI of a pavement section can then be obtained by combining the fuzzy Roadmeter Reading (RR) of a section (as developed using the techniques presented above) with the PSR-RR matrix, resulting in a membership function for the PSI of the section. This operation can be facilitated by developing simple mathematical relationships between the characteristics of the PSI and RR fuzzy sets. These relationships are given in Appendix D for the four pavement categories under consideration.

Summary

At this stage a knowledge base has been obtained for PSR-RR relationships. A different PSR-RR knowledge base was formed for each pavement type. They were developed from existing data provided by IDOH (Partridge, 1982) and are now computerized under a matrix form (or mathematical relationships as given in Appendix D). It is suggested to update the PSR-RR relationships as more panel ratings become available. If numerical problems are encountered, the techniques described in this section can be used efficiently to solve them. If sufficient data points are available, these problems will not arise. It should be emphasized that no additional effort is needed from an engineer to use this system. The user can find the Pavement Serviceability Index (PSI) of pavement sections provided that Roadmeter Readings (RR) are

measured. The computer program "Road.f" performs this operation without user's intervention except for input data for roadmeter readings. A subsequent chapter will show how the resulting PSI values can be used for initial screening of pavements with respect to their rideability.

CHAPTER 2

PAVEMENT EVALUATION 2 : SKID, DEFLECTION AND DISTRESS

In this chapter, the different sources of variability for the Friction Number (FN), Dynaflect reading and Pavement Condition Rating (PCR) are investigated. The results obtained from the questionnaires submitted to experts to analyze these variabilities are summarized and discussed.

Skid-tester variability

In the State of Indiana, the skid resistance of pavements is measured by a skid-tester. The measured coefficient of friction is multiplied by a hundred to give a friction number between 0 and 100. Several variables affect the FN measurements and introduce uncertainty in the recorded data. Analytical techniques (Mohan, 1978, and Metwali, 1981) have been suggested to handle this uncertainty using statistical methods. Currently, the average of a specified number of spot tests is treated as the FN of the section. It is important to realize, that although there is some random uncertainty involved, system uncertainty also plays an important role. Several sources of variation fall under this category: changes in ambient temperature, rainfall and vehicle speed. These factors influence pavement evaluation in a manner

that can not be statistically predicted. Therefore, they are not incorporated in the existing models.

Questionnaire No.3 was submitted to highway engineers to gather information related to these variabilities and to the acceptable friction number required to insure traffic safety. Responses obtained from eight experts are included in Appendix A. Two sources of variability were considered in the questionnaire: climatic changes and vehicle speed changes. Two of the experts indicated that they did not have the necessary experience to answer the question related to climatic changes. The ranges of variation proposed by the six other experts were averaged for each pavement type. The average ranges of variation are summarized in Table 2.1. These variations were in the order of $\pm 6\%$ of the central value (i.e., range of variation equal to $\pm 6\%$ of the measured value should be used on both sides of this value). Four of the experts did not agree with the idea that there is a variation in the FN measurements due to vehicle speed changes. The four other experts indicated ranges of variation of $\pm 0.5\%$ for all four pavement types.

It should be recognized that the number of experts was not sufficient to draw definitive conclusions with regard to the influence of climatic and vehicle speed changes. Furthermore, this small sample indicates that there may not be complete agreement among highway experts. This is an area which would obviously require more data before implementation of the proposed methodology.

Table 2.1. Variability of FN Due to Climatic Changes.

<u>Type of pavement</u>	<u>Range of variation</u>
Asphalt	$\pm 6.5\%$
Overlay	$\pm 6.5\%$
CRCP	$\pm 5.8\%$
JRCP	$\pm 5.8\%$

It was proposed (Gunaratne, 1984) to introduce the variability related to the FN measurements due to climatic and vehicle speed changes by substituting the discrete FN with a fuzzy set. The techniques (kernels of fuzzification) to include more than one source of variation around the central (measured) value were described by Gunaratne (1984) and will not be repeated here. An example of a fuzzy FN for an asphalt pavement section is given in Figure 2.1. This fuzzy FN was formed using a central (measured) FN of 45. Ranges of variation of 6.5% and $\pm 0.5\%$ were introduced for the effects of climatic and vehicle speed changes, respectively. A π curve (Appendix B) was used to find the corresponding membership values. Note that, once the ranges of variation are obtained from highway experts, the computer program "Skid.f" can obtain the fuzzy set corresponding to any measured FN without further user's intervention.

Dynaflect variability

It has been observed that repeated trials of the Dynaflect result in different readings at the same location. Presently the average of the readings of a specified number of tests is taken as the Dynaflect reading, and the inherent imprecision is treated as random uncertainty (Mohan, 1978). Gunaratne (1984) showed that, by introducing a "suitable" interval instead of a discrete reading, fuzzy sets theory can be used to provide a better representation of this imprecision. Deflections are easily measured at the center of pavements but they must be converted to

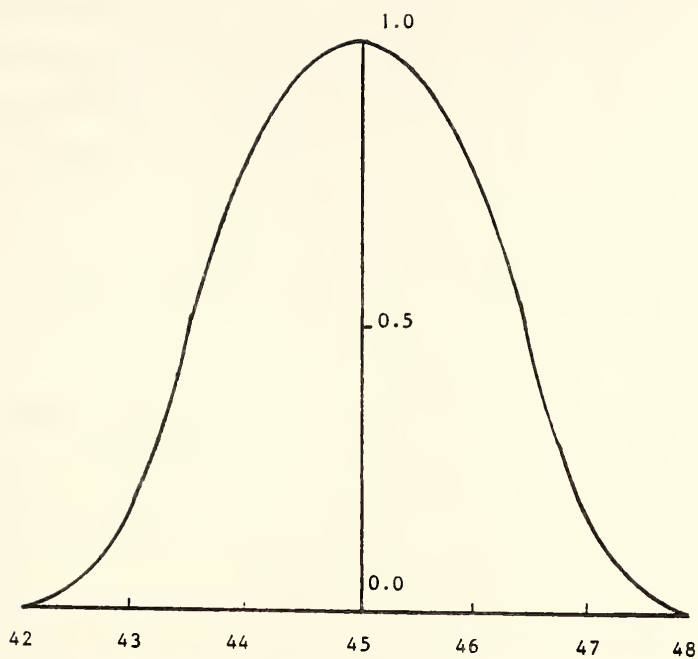


Figure 2.1. Typical Fuzzy Friction Number.

those at the edge, because edge deflections are more critical for design purposes. Since it is difficult to identify the edge of a deteriorated pavement, it was proposed (Gunaratne, 1984) to attach a certain tolerance to the "Edge deflection/Center deflection" ratio. A significant seasonal variation in deflection values has also been observed (Metwali, 1981), the more critical deflections being measured during the spring thaw period. Most measurements are taken during the fall season and, thus, such values need to be converted to spring values. Hence, it is also proposed to attach a tolerance level to the "Spring deflection/Fall deflection" ratio.

Questionnaire No.4 was submitted to highway engineers to gather information related to the variabilities of the dynaflect measurements and uncertainty associated with the conversion factors (Appendix A). The main source of variability considered in this questionnaire was the inability to repeat a reading at a particular test location. Three out of seven experts indicated that they did not have the necessary experience to answer the question related to the dynaflect variation at the same location on repeated trials. The ranges of variation proposed by the other experts were averaged for each pavement type and they are given in Table 2.2. These variations are of the order of 4.0% of the measured value for asphalt and overlay pavements, and of $\pm 2.5\%$ for JRC and CRC pavements.

Six out of the seven engineers did not have the experience needed to answer the remaining parts of this questionnaire,

Table 2.2. Dynaflect Reading Variation

<u>Type of pavement</u>	<u>Dynaflect reading variation</u>
Asphalt	$\pm 4.0\%$
Overlay	$\pm 4.0\%$
CRCP	$\pm 2.5\%$
JRCP	$\pm 2.7\%$

related to the "Edge deflection/Center deflection", "Spring deflection/Fall deflection" ratios and the tolerance associated with them. This is mainly because dynaflect measurements are not conducted on a routine basis in Indiana, but only in a small number of projects for establishing undersealing criteria. Thus, implementation of the techniques proposed by Gunaratne (1984) will require that more information be gathered on the range of variation and on the conversion factors. The remarks made previously with regard to the small sample for Questionnaire No.3 also apply to this questionnaire. Therefore, if Dynaflect measurements are to be included in future implementation of the prioritization scheme, the related questionnaires will have to be submitted to individuals having experience with the Dynaflect.

Variability in Pavement Condition Rating (PCR)

The Indiana Department of Highways procedure for distress surveys recommends that a crew examines and estimates the extent and severity of different pavement defects. The survey is performed for a selected length of a section at a designated mile post. Instruction sheets are available for both flexible and rigid pavements to assist the crew in assigning ratings to the defect types. The Pavement Condition Rating (PCR) is obtained by subtracting the sum of defect ratings from a maximum PCR of 100. Human based uncertainty enters the PCR by way of imprecision of measurements and subjective judgements. In questionnaire No.5 the importance of this uncertainty for various kinds of distress

was quantified by attaching a range of variation to each distress rating.

Nineteen out of twenty two experts who were contacted answered questionnaire No.5. Eighteen of them agreed with the concept of attaching a range of variation to the distress rating for extent of the defects. Furthermore, sixteen of them were in agreement with the concept of having a range of variation attached to the distress rating for severity of the defects. All the responses are included in Appendix A. The average ranges of variation obtained from the responses are given in Table 2.3. These results indicated that the ranges obtained for the different kinds of distress of a given pavement type (flexible or rigid) were identical. For the extent of distress the variability obtained was of the order of ± 1.1 for each distress type in a scale of 0.0 to 10.0. For the severity of each distress type, a variability of the order of ± 1.4 was obtained.

It can be shown that the fuzzy PCR obtained by considering the different distress types and the corresponding ranges of variations separately is identical to the one obtained by using the summation of the distress ratings. In the latter case a range of variation equal to the summation of the ranges applied for each kind of distress is introduced. This observation is further demonstrated in Appendix C using a numerical example. Therefore, the global ranges of variation shown in Table 2.3, according to pavement type and extent or severity of the distress, can be used to form the fuzzy PCR. These ranges are attached to the summation

Table 2.3. Range of Variation for PCR Values.

<u>Extent (0 to 10)</u>		<u>Severe (0 to 10)</u>	
<u>Flexible Pavements</u>		<u>Flexible Pavements</u>	
Alligator cracks	±1.14	Transverse cracks	±1.47
Block cracking	±1.19	Longitudinal cracks	±1.33
Shoving	±1.14	Patching	±1.40
Patching	±1.14		
Total = ±4.61		Total = ±4.20	
<u>Rigid Pavements</u>		<u>Rigid Pavements</u>	
D-cracking	±1.19	Pavement break-up	±1.60
Patching	±1.14	Patching	±1.40
Slab break-up	±1.19	Transverse cracks	±1.40
Pumping	±1.13	Longitudinal cracks	±1.27
Faulting	±1.11	D-cracking	±1.63
Total = ±5.76		Total = ±7.30	

of distress ratings and the membership function of the PCR can be obtained from the computer program "Dist.f".

An example of a fuzzy PCR for a flexible pavement section is given in Figure 2.2. This fuzzy PCR was formed using a summation of distress ratings equal to 25 (central value) and ranges of variation of ± 4.61 and ± 4.20 for extent and severity of the defects, respectively.

Summary

In this chapter, the ranges of variation for the friction number, dynaflect measurements and distress ratings were obtained using expert opinion. The recommended ranges of variation become part of the expert knowledge base. The fuzzy FN, dynaflect reading and PCR can be obtained for any number of sections using the measured values or ratings (central values), the stored knowledge base, and the related computer programs developed for that purpose. Future implementation of the proposed methodology would require that a larger sample of experts be contacted, especially to gather more information regarding FN and Dynaflect measurements.

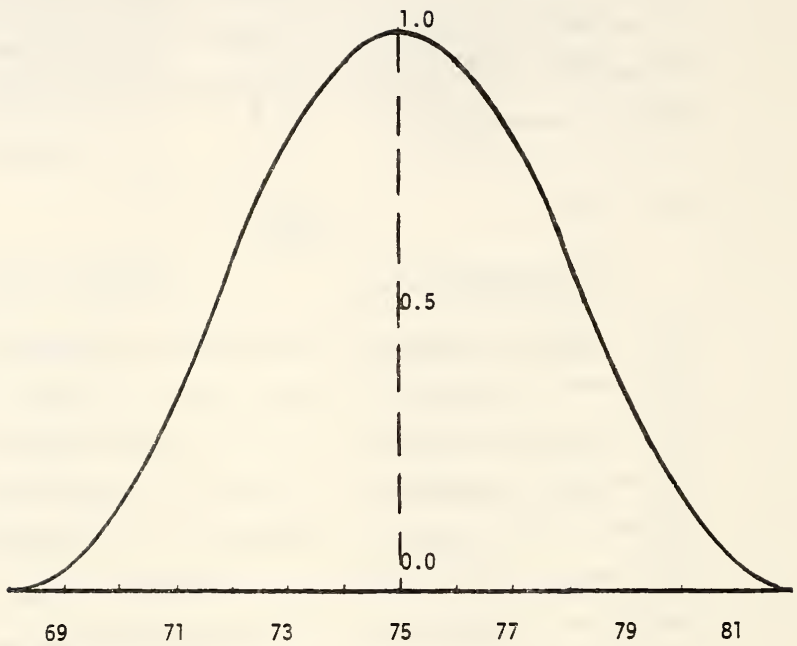


Figure 2.2. Typical Fuzzy Pavement Condition Rating.

CHAPTER 3

DATA BASE RELATED TO THE PAVEMENT SECTIONS TO BE RANKED

In the following chapters, the techniques developed to rank pavements according to maintenance priorities will be presented. The knowledge base (expert information) which was acquired during this study is also discussed.

To facilitate the discussion and to provide a typical example of application of the methodology, a data set provided by the IDOH Research and Training Center will be used (Kercher, 1984). This data set provides information about 81 pavement sections of four types: Asphalt pavements, Overlays, Jointed Reinforced Concrete Pavements (JRCP) and Continuously Reinforced Concrete Pavements (CRCP). When this information is used in the following chapters, reference will be made to Tables 3.1 to 3.4 which summarize the data. The following characteristics and limitations of the data are also of interest:

1) Remarks common to all pavement types.

a) Surface, route, RR, FN, ADT, PCR and location are indicated for each pavement section in Tables 3.1 to 3.4.

b) The PCR values were obtained either in 1982 or in 1983, as indicated in parenthesis in the first column of each table.

c) All ADT values were obtained in 1982.

d) FN measurements were conducted during the year shown in parenthesis. If the year is not specified, they were obtained the same year the PCR was measured.

e) Information regarding year of construction, Structural Number (SN), percentage of trucks is only provided for interstate pavements.

f) Dynaflect measurements were only available for very few pavement sections and therefore were not included in the prioritization scheme, although they can be included in future implementation if data becomes available.

2) Asphalt pavements

a) Data were provided for 10 sections.

b) None of the asphalt sections provided were from the interstate network.

3) Overlay pavement sections

a) Data were provided for 30 sections.

b) Only three of the pavement sections were from the interstate network.

4) JRCF sections

a) Data were provided for 28 sections.

b) All but one section were interstate pavement sections.

5) CRCP sections

a) Data were provided for 13 sections.

b) All sections were from Interstate 65.

Table 3.1. Data Summary for Asphalt Pavement Sections.

(*1)	(*2)	(*3)							
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr.	Str.	No % Trucks
1) Asphalt (1982)	SR 205	1669	63.8 (1980)	1313	86.50 (5.01)	Ft. Wayne RS-10793 (7.56mi)			Not available
2) Asphalt (1982)	US 231	895	37	3200	89.00 (4.29)	Crawford. RS-10355 (5.27 mi)		"	
3) Asphalt (1982)	SR-59	794	57	633	87.17 (1.94)	Crawford. SR-10790 (5.20 mi)		"	
4) Asphalt (1982)	SR-9 SB	1783	42.5 (40) 42.8 (50)	3209 (dir)	78.00 (3.32)	Greenfield RS-9784 (11 mi)		"	
5) Asphalt (1982)	SR-9 SB	1661	42.5 (40) 42.8 (50)	1600 (dir)	78.67 (1.53)	Greenfield RS-9784 (11 mi)		"	

(*1) Year PCR was obtained.

(*2) Velocity of vehicle for the friction measurement.

(*3) Year friction number measured.

(*3) St. deviation for PCR.

Table 3.1. (Continued).

(*1)		(*2)		(*3)		Con. Yr. Str. No % Trucks
Surface	Route	RR	FN	ADT	PCR	
6) Asphalt (1982)	SR-9 SB	1661	42.5 (40) 42.8 (50)	2406	80.67 (4.16)	Greenfield RS-9784 (11 mi) Not available
7) Asphalt (1982)	US.36 EB	756	52.0 (40) 52.1 (50)	1172 (dlr)	90.0 (0.0)	Greenfield RS-11058 (12.7 mi) "
8) Asphalt (1982)	US.36 EB	756	52.0 (40) 52.1 (50)	900 (dlr)	89.20 (2.35)	Greenfield RS-11058 (12.7 mi) "
9) Asphalt (1982)	SR-64	1417	41.3	9000	88.75 (9.45)	Vincennes RS-10671 (8.89 mi) "
10) Asphalt (1982)	SR-66	1590	40.9 (1977)	14500	90.83 (2.40)	Vincennes RS-10482 (5.54 mi) "

(*1) Year PCR was obtained.

(*2) Velocity of vehicle for the friction measurement.

(*3) Year friction number measured.

(*3) St. deviation for PCR.

Table 3.2. Data Summary for Overlay Pavement Sections.

(#1)	(#2)			(#3)			
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr. Str. No % Trucks
1) Overlay (1982)	US 20	1202	44.6 (1979)	2930 (Dir)	88.31 (2.43)	Ft.Wayne RS-10650 (12.85 mi)	Not available
2) Overlay (1982)	US 24	1707	44.3	3485 (Dir)	79.92 (6.25)	Ft.Wayne RS-9592 (12.85 mi)	"
3) Overlay (1982)	US 40EBL	1193	55	1512	93.8 (3.11)	Crawford. RS-10518 (4.11 mi)	"
4) Overlay (1982)	US 41	697	38	1775	88.27 (1.90)	Crawford. RS-10044 (10.84 mi)	"
5) Overlay (1982)	US 40 EB	660	56.9 (40) 53.1 (50)	2352 (Dir)	90.11 (1.54)	Greenfield RS-11055 (13.3 mi)	"

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#3) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.2. (Continued).

(#1)	(#2)			(#3)			
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr. Str. No % Trucks
6) Overlay (1982)	US 40 EB	660	56.9 (40) 53.1 (50)	1700 (Dir)	91.33 (1.15)	Greenfield RS-11055 (13.3 ml)	Not available
7) Overlay (1982)	US 40 EB	660	Unav.	6400 (Dir)	87.50 (4.95)	Greenfield RS-11055 (13.3 ml)	"
8) Overlay (1982)	SR 28 WB	1118	46.4 (40) 42.2 (50)	2633 (Dir)	90.86 (3.13)	Greenfield RS-11513 (19.8 ml)	"
9) Overlay (1982)	SR 28 WB	1467	46.4 (40) 42.2 (50)	2235 (Dir)	88.17 (3.13)	Greenfield RS-11513 (19.8 ml)	"
10) Overlay (1982)	US 35 NB SR 28 WB	1133	43.1 (40) 36.7 (50)	3606 (Dir)	88.17 (3.76)	Greenfield RS-11513 (19.8 ml)	"

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#3) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.2. (Continued).

(#1)	(#2)		(#3)			
Surface	Route	RR	FN	ADT	PCR	Location
11) Overlay (1982)	SR 56	1119	42.6	4000	84.33 (1.94)	Vincennes RS-10670 (8.41 mi)
12) Overlay (1982)	SR 67	598	55	2800	90.75 (2.19)	Vincennes RS-11908 (7.2 mi)
13) Overlay (1982)	SR 46	1397	29.7 (40) 28.7 (50) (1983)	6350	91.0 (7.28)	Seymour RS-10369 (7.9 mi)
14) Overlay (1982)	US 31	678	53.9 (40) 48.4 (50) (1983)	3483	91.67 (2.65)	Seymour RS-10662 (8.4 mi)
15) Overlay (1982)	SR 252	971	46.1 (40) 44.8 (50) (1983)	2900	87.78 (1.92)	Seymour RS-11067 (8.8 mi)

Not available

"

"

"

"

- (#1) Year PCR was obtained.
 (#2) Velocity of vehicle for the friction measurement.
 (#2) Year friction number measured.
 (#3) St. deviation for PCR.

Table 3.2. (Continued).

(#1)	(#2)	(#3)					
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr. Str. No % Trucks
16) Overlay (1982)	US 150	1512	?	2388	84.64 (5.95)	Seymour RS-9994 (11.4 ml)	Not available
17) Overlay (1982)	SR 29	718	48.7 (40)	1525	91.5	La Porte RS-10799 (12.8 ml)	"
18) Overlay (1982)	SR 29	718	48.7 (40)	1856	93.13 (1.93)	La Porte RS-10799	"
19) Overlay (1982)	SR 29	718	48.7 (40)	2225	92.25 (4.35)	La Porte RS-10799	"
20) Overlay (1982)	SR 29	718	48.7 (40)	1881	92.75 (3.18)	La Porte RS-10799	"

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#2) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.2. (Continued).

(#1)	(#2)	(#3)					
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr. Str. No % Trucks
21) Overlay (1982)	SR 29	718	48.7 (40)	1796	94.00 (2.83)	La Porte RS-10799	Not available
22) Overlay (1982)	US 6	1685	36.5 (40)	3283	87.33 (4.80)	La Porte RS-9992 (5.25 ml)	"
23) Overlay (1982)	US 6	1136	38.3 (40) 35.5 (50) (1983)	2475	81.5 (8.85)	La Porte RS-10533 (11.8 ml)	"
24) Overlay (1982)	US 6	1136	38.3 (40) 35.5 (50) (1983)	2313	83	La Porte RS-10533 (11.8 ml)	"
25) Overlay (1982)	US 6	1136	38.3 (40) 35.5 (50) (1983)	2359	84.81 (2.28)	La Porte RS-10533 (11.8 ml)	"

- (#1) Year PCR was obtained.
 (#2) Velocity of vehicle for the friction measurement.
 (#2) Year friction number measured.
 (#3) St. deviation for PCR.

Table 3.2. (Continued).

(#1)	(#2)		(#3)					
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr. Str.	No % Trucks
26) Overlay (1982)	US 421 N 1489	Not Tested	712	81.11 (3.44)	La Porte	RS-10659	Not available	
27) Overlay (1982)	US 421 N 1489	Not Tested	2221	84.33 (0.58)	La Porte	RS-10659	"	
28) Overlay (1983)	I-69 SBL 1113	58.8 (40) 54.4 (50) (1983)	7362	82.0 (4.56)	Ft. Wayne	R-11664 (5.7 mi)	1978	10.0 38.0
29) Overlay (1983)	I-74 WBL 1312	36.4 (40) 37.9 (50) (1983)	5750	94.6 (3.27)	Seymour	R-11856 (9.4 mi)	1979	10.0 26.0
30) Overlay (1983)	I-65 SBL 996	30. (40) (1983)	15387	88.8 (2.68)	Crawfordsv.	R-9589 (4.9 mi)	1975	11.0 33.0

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#2) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.3. Data Summary for JRCP Sections.

(#1)	(#2)	(#3)	Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr.	Str. No	% Trucks
1)	JRCP (1983)	37.2 (40) 37.3 (50) (1983)	2004	I-74 WBL	6450	92.75 (2.5)	Seymour R-5434 (2.6 mi)	1963	10.0	26.0		
2)	JRCP (1983)	36 (40) 36.3 (50) (1983)	2190	I-74 WBL	6450	83.83 (8.18)	Seymour R-5481 (5.8 mi)	1963	10.0	26.0		
3)	JRCP (1983)	31.7 (40) 33.2 (50) (1983)	2565	1-74 EBL	6450	85.83 (5.19)	Seymour R-5481 (5.8 mi)	1963	10.0	26.0		
4)	JRCP (1983)	32.4 (40) (1983)	2430	I-74 EBL	6450	84.50 (5.20)	Seymour R-5434 (2.9 mi)	1963	10.0	26.0		
5)	JRCP (1983)	38.6 (40) (1983)	1611	I-94 EBL	18300	93.50 (1.73)	La Porte R-7933 (3.5 mi)	1970	9.0	36.0		

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#2) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.3. (Continued).

(#1)			(#2)			(#3)			
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr.	Str.	No % Trucks
6) JRCP (1983)	I-94 WBL	1510	41.7 (40) (1983)	18300	94.20 (1.09)	La Porte R-7933 (3.5 ml)	1970	9.0	36.0
7) JRCP (1983)	I-65 SBL	1642	41.2 (40) (1983)	8100	82.75 (12.5)	La Porte R-7198 (3.3 ml)	1968	10.0	33.0
8) JRCP (1983)	I-74 EBL	1707	42 (40) (1983)	3925	88.00 (1.90)	Crawfordsv. R-629 (5.3 ml)	1968	10.0	40.0
9) JRCP (1983)	I-74 EBL	1472	41.5 (40) 38.9 (50) (1983)	3763	91.71 (3.55)	Crawfordsv. R-620	1965	10.0	40.0
10) JRCP (1982)	SR 28 WB	1467	46.4 (40) 42.2 (50)	2262 (Dir)	94	Greenfield R-5819 I-69, SR28 interc.	Not available		

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#3) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.3. (Continued).

(#1)	(#2)	(#3)							
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr.	Str.	No % Trucks
11) JRCP (1983)	I-65 NBL	1300	32.4 (40)	14150	81.00 (2.16)	Greenfield R-5856 (3.2 ml)	1964	10.0	8.0
12) JRCP (1983)	I-70 WBL	1585	?	39000	98.00 (0.0)	Greenfield ? (2.2 ml)		Not available	
13) JRCP (1983)	I-70 WBL	1923	?	45000	98.0 (0.0)	Greenfield R-1034 (2.5 ml)		"	
14) JRCP (1983)	I-74 EBL	1727	36 (40) 36.6 (50) (1981)	7650	83.38 (3.25)	Greenfield R-4399 (7.1 ml)	1961	10.0	26.0
15) JRCP (1983)	I-74 EBL	2159	37 (40) 33.1 (50) (1981)	5700	78.38 (5.50)	Greenfield R-4614 (7.5 ml)	1961	10.0	26.0

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#2) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.3. (Continued).

	(#1)	(*2)			(*3)					
	Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr.	Str. No	% Trucks
16)	JRCP (1983)	I-74 EBL	3045	36.9 (40) (1981)	5550	76.33 (1.15)	Greenfield R-5434 (2.5 mi)	1963	10.0	26.0
17)	JRCP (1983)	I-74 WBL	2219	36.1 (40) 33.7 (50) (1981)	5550	84.00 (7.79)	Greenfield R-5434 (2.8 mi)	1963	10.0	26.0
18)	JRCP (1983)	I-74 WBL	1869	33.7 (40) 33.4 (50) (1981)	5700	78.88 (4.79)	Greenfield R-4614 (7.5 mi)	1961	10.0	26.0
19)	JRCP (1983)	I-74 WBL	1787	37.4 (40) 34.1 (50) (1981)	7650	75.22 (10.33)	Greenfield R-4399 (7.3 mi)	1961	10.0	26.0
20)	JRCP (1983)	I-74 WBL	1417	40 (40) (1981)	25700	84.5 (0.71)	Greenfield R-5969	1961	10.0	26.0

(*1) Year PCR was obtained.

(*2) Velocity of vehicle for the friction measurement.

(*3) Year friction number measured.

(*3) St. deviation for PCR.

Table 3.3. (Continued).

	(#1)		RR	FN	ADT	PCR	Location	Con. Yr.	Str.	No % Trucks
	Surface	Route								
20)	JRCP (1983)	I-74 WBL	1417	40 (40) (1981)	25700	84.5 (0.71)	Greenfield R-5969	1961	10.0	26.0
21)	JRCP (1982)	I-69 NBL	2045	38.3 (1983)	9525	75	R-5842	1963	10.0	38.0
22)	JRCP (1982)	I-69 NBL	2141	37.6 (1983)	9525	87.50 (2.65)	R-5814	1964	10.0	38.0
23)	JRCP (1982)	I-69 NBL	2150	37.2 (1983)	9525	81.00 (3.46)	R-5843	1965	10.0	38.0
24)	JRCP (1982)	I-69 NBL	2715	38.4 (1983)	7312	79.67 (4.32)	R-5857	1963	10.0	38.0
25)	JRCP (1982)	I-69 SBL	2627	40.3 (1983)	7312	68.33 (3.39)	R-5857	1963	10.0	38.0

(*1) Year PCR was obtained.

(*2) Velocity of vehicle for the friction measurement.

(*2) Year friction number measured.

(*3) St. deviation for PCR.

Table 3.3. (Continued).

Surface	Route	RR	(*2)		ADT	PCR	Location	Con. Yr. Str. No % Trucks	
			(#1)	(#3)					
26) JRCP (1982)	I-69 SBL	1994	31.1 (1983)		9525	71.33 (1.15)	R-5843	1965	10.0 38.0
27) JRCP (1982)	I-69 SBL	2535	39.3 (1983)		9525	58.75 (4.99)	R-5814	1964	10.0 38.0
28) JRCP (1982)	I-69 SBL	2133	40.3 (1983)		9525	67	R-5842	1963	10.0 38.0

(*1) Year PCR was obtained.

(*2) Velocity of vehicle for the friction measurement.

(*3) Year friction number measured.

(*3) St. deviation for PCR.

Table 3.4. Data Summary for CRCP Sections.

(#1)	(#2)	(#3)							
Surface	Route	RR	FN	ADT	PCR	Location	Con. Yr.	Str. No	% Trucks
1) CRCP (1983)	I-65 SBL	1663	9.9 (40) (1983)	11262	90.0 (8.49)	Crawford, R-7913 (3.6 ml)	1971	11.0	33.0
2) CRCP (1983)	I-65 SBL	1653	42.7 (40) 37.7 (50) (1983)	8125	91.57 (4.39)	Crawford, R-7714 (5.5 ml)	1970	11.0	33.0
3) CRCP (1983)	I-65 NBL	1501	42.7 (40) (1983)	8560	92.5 (5.82)	Crawford, R-7633 (5.2 ml)	1970	11.0	33.0
4) CRCP (1983)	I-65 SBL	1504	41.9 (40) 38.9 (50) (1983)	8560	89.14 (8.76)	Crawford, R-7422 (6.0 ml)	1971	11.0	33.0
5) CRCP (1983)	I-65 SBL	1854	41.3 (40) (1983)	8560	89.67 (4.84)	Crawford, R-7633 (5.2 ml)	1970	11.0	33.0

(#1) Year PCR was obtained.

(#2) Velocity of vehicle for the friction measurement.

(#3) Year friction number measured.

(#3) St. deviation for PCR.

Table 3.4. (Continued).

	(*1)		(*2)		(*3)		Con. Yr. Str. No % Trucks
	Surface	Route	RR	FN	ADT	PCR	
6)	CRCP (1983)	I-65 SBL	1764	43.4 (40) (1983)	11262	90.0 (3.87)	1970 11.0 33.0 Crawford. R-7677 (4.4 ml)
7)	CRCP (1982)	I-65 NBL	1097	39.5 (1983)	13988	91.25 (2.87)	1971 11.0 36.0 R-7912
8)	CRCP (1982)	I-65 NBL	1586	36.7 (1983)	18000	86.50 (1.73)	1971 11.0 36.0 R-8001
9)	CRCP (1982)	I-65 NBL	1324	41.1 (1983)	18000	92 (0.0)	1972 11.0 36.0 R-8440
10)	CRCP (1982)	I-65 SBL	1096	44.1 (1983)	18000	95 (0.0)	1972 11.0 36.0 R-8440

(*1) Year PCR was obtained.

(*2) Velocity of vehicle for the friction measurement.

(*3) Year friction number measured.

(*3) St. deviation for PCR.

Table 3.4. (Continued).

	(*1)		(*2)		(*3)		Location	Con. Yr.	Str. No	% Trucks
	Surface	Route	RR	FN	ADT	PCR				
11)	CRCP (1982)	I-65 SBL	1715	40 (1983)	18000	86.4 (0.9)	R-8001	1971	11.0	36.0
12)	CRCP (1982)	I-65 SBL	1192	40.4 (1983)	13988	84.6 (5.3)	R-7912	1971	11.0	36.0
13)	CRCP (1982)	I-65 SBL	1379	36.4 (1983)	11350	95.0	R-8221	1971	10.0	36.0

(*1) Year PCR was obtained.

(*2) Velocity of vehicle for the friction measurement.

(*2) Year friction number measured.

(*3) St. deviation for PCR.

CHAPTER 4

DECISION MAKING 1: INITIAL SCREENING OF PAVEMENT SECTIONS

The Pavement Management System requires traffic and performance data. Traffic data is obtained by conducting traffic surveys to evaluate the Annual Daily Traffic (ADT). Performance data is obtained by evaluating the roughness (rideability), skid resistance, distress manifestation and structural adequacy of pavements.

The first stage of the decision making process involves screening sections by comparing pavement data (PSI and FN) with acceptability levels. Information related to the acceptability levels for serviceability and skid resistance is obtained from responses given by the experts to questionnaires Nos.2 and 3. This constitutes part of the knowledge base needed to rank the pavements. In this chapter, these acceptability levels are presented and discussed, and the screening operation is illustrated using the data set given in chapter 3.

Acceptable Serviceability Range

It was proposed by Gunaratne (1984) to represent the acceptable serviceability by using a domain (range) of PSI values where it is believed to a certain extent that the pavement has acceptable serviceability. For this purpose, the experts were asked (Questionnaire No.2) to provide the level of PSI above which the pavement sections are considered to have acceptable serviceability. The ratio of the number of experts considering a particular PSI value in the acceptable range to the total number of experts is obtained for each PSI value. This ratio represents the membership value for that PSI value within the Acceptable Serviceability Range (ASR), thus indicating the degree of belief that the value is acceptable.

A typical acceptability range obtained for primary pavements is given in Figure 4.1. A stepwise membership function was obtained, indicating experts' opinions on the acceptable level ranging between 2.5 and 3.0. The stepwise membership function was modified to a straight line using linear regression. A linear membership function is recommended to have a gradual transition zone for the ASR. This relation implies that there is a range of PSI values where it is uncertain if the pavement section has acceptable PSI. The serviceability level above which a pavement adequately serves the users does not depend on the pavement type but depends on the usage of the road (i.e., primary or secondary roads). The ASR for secondary pavements is shown on Figure 4.2.

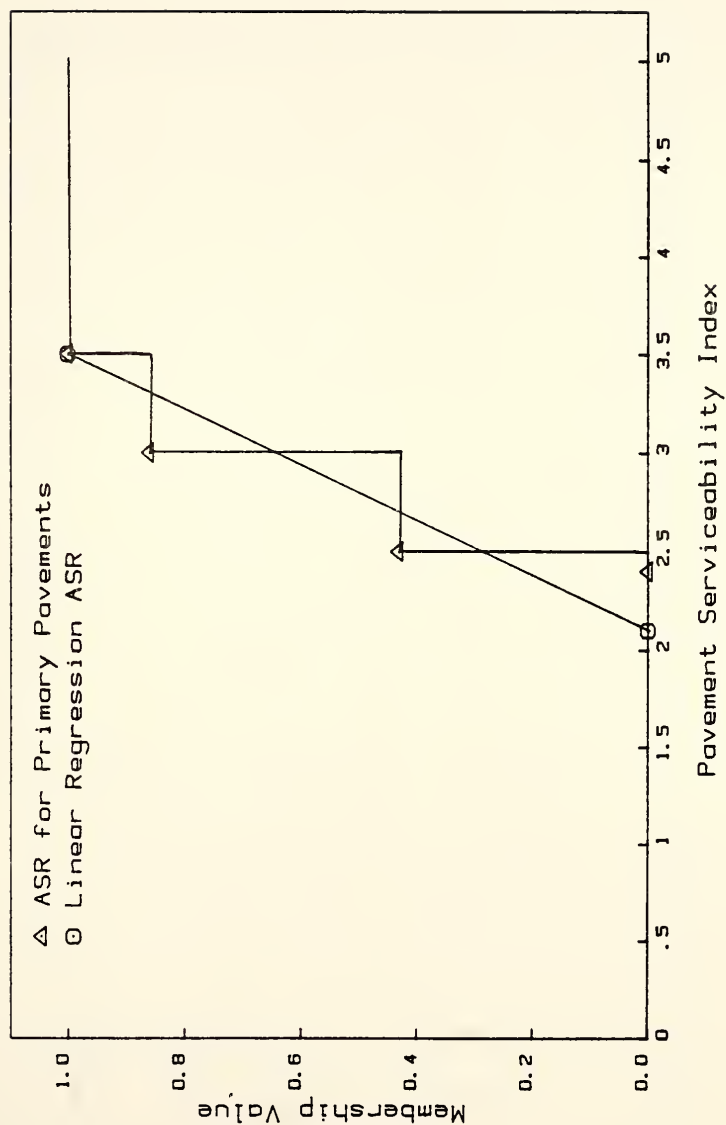


Figure 4.1. Acceptable Serviceability Range for Primary Pavements.

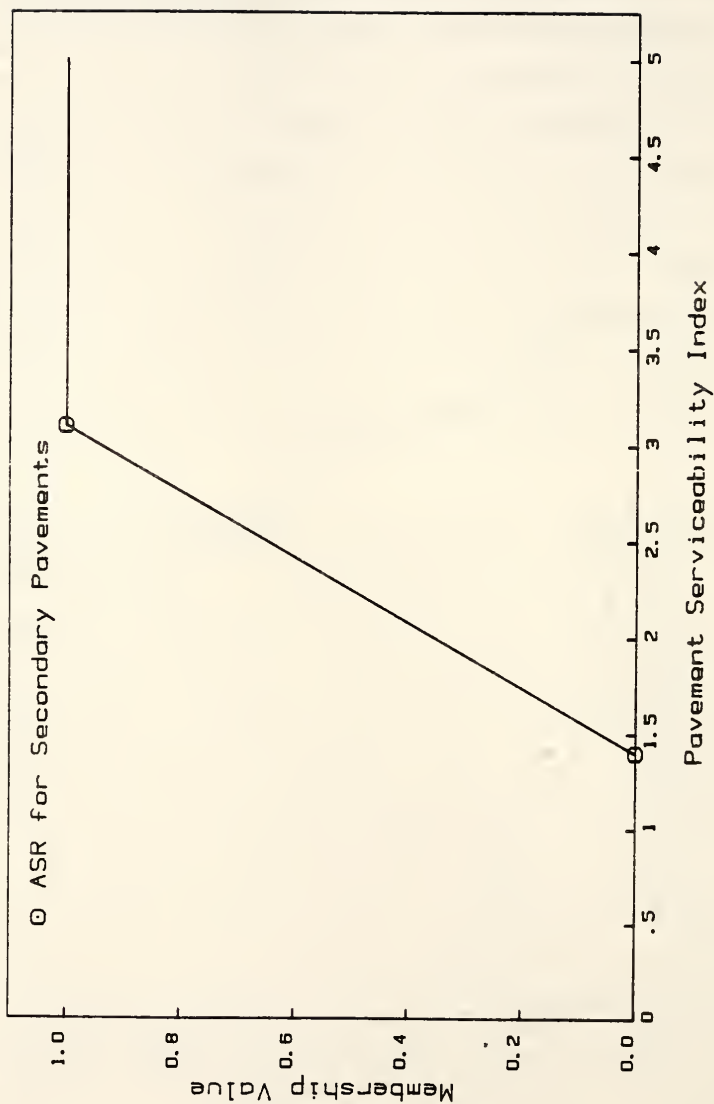


Figure 4.2. Acceptable Serviceability Range for Secondary Pavements.

Nonacceptable Serviceability Range

In order to allow for some flexibility in classifying the pavements with respect to their serviceability, a nonacceptability range is also introduced. The serviceability levels below which a pavement does not serve its purpose adequately are included in the Nonacceptable Serviceability Range (NASR). The following sections will show how the NASR enters the screening criteria. Including both acceptable and nonacceptable ranges in this study imply that there is a domain of PSI values where experts' opinions on what is acceptable or nonacceptable are imprecise.

Questionnaire No.2 included questions with regard to the nonacceptable levels, and the responses of the experts to those questions were converted to a nonacceptable range following the procedure used previously for the acceptable level. The membership values for the NASR are shown in Figures 4.3 and 4.4.

Acceptable and Nonacceptable Friction Number

Continuous traffic loads result in a decrease in the skid-resistance of a pavement because of wearing of the surface. The acceptable friction number is defined as the value of friction above which the pavement does not present any skid hazard. As was the case for acceptable serviceability, the evaluation of an acceptable friction number is difficult and requires judgment. Thus, it will be represented by an acceptable friction range

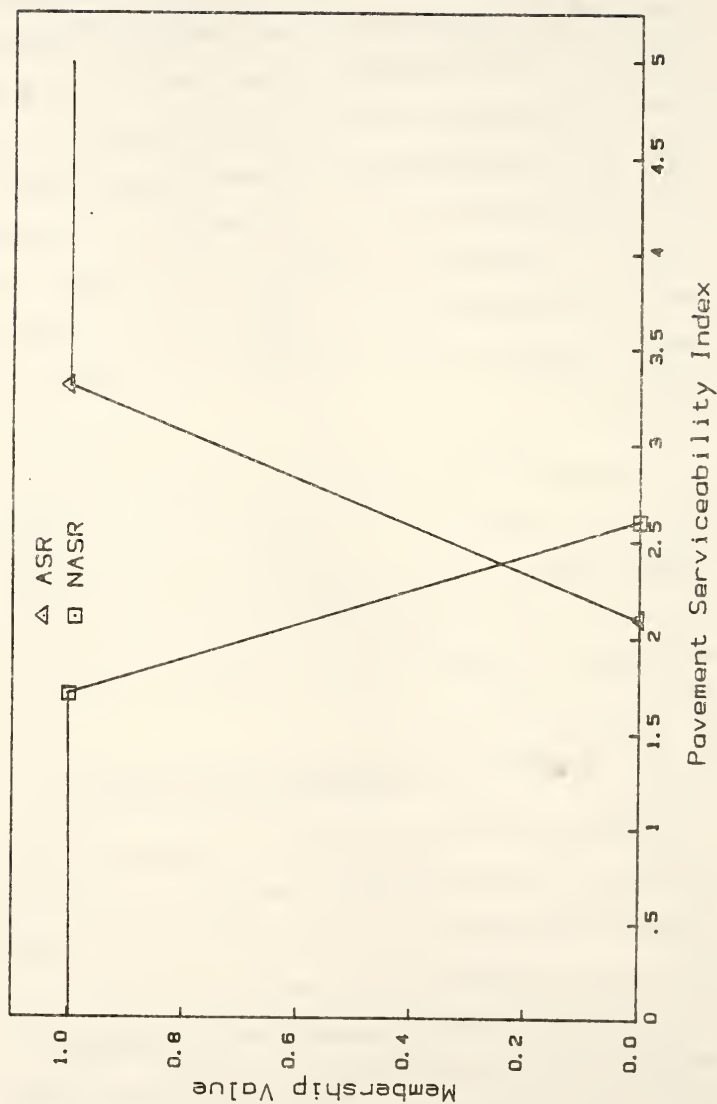


Figure 4.3. Acceptable and Nonacceptable Serviceability Ranges for Primary Pavements.

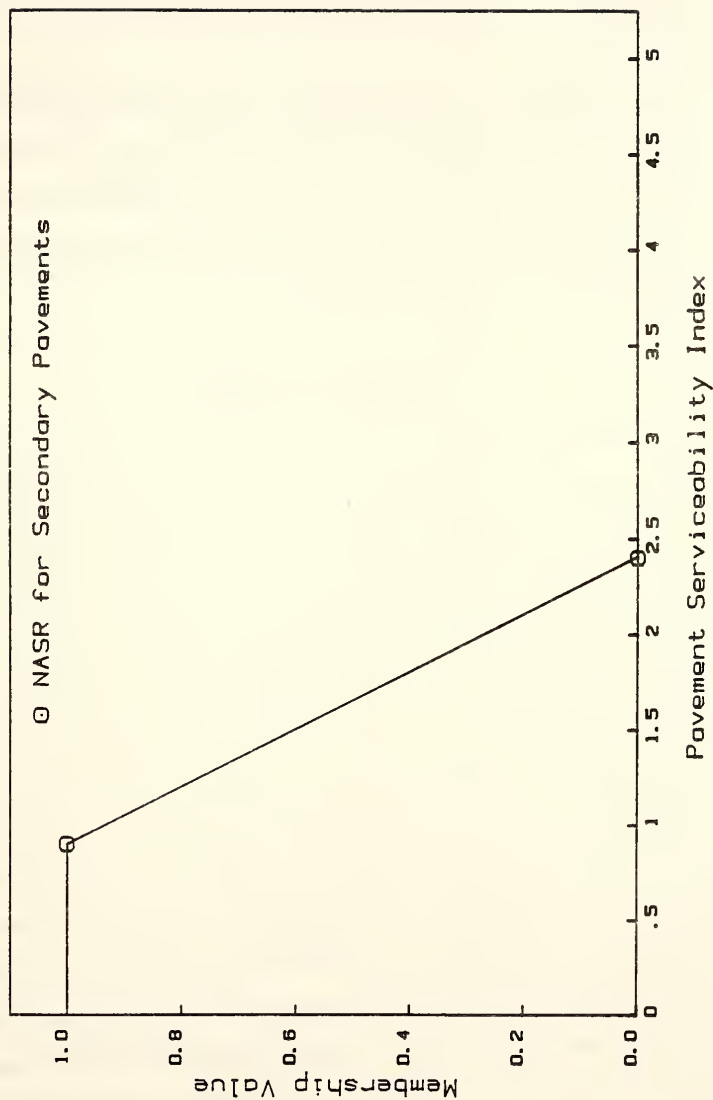


Figure 4.4. Nonacceptable Serviceability Range for Secondary Pavements.

obtained from experts' opinion. A nonacceptable friction number is also introduced as the value of friction number below which rehabilitation is required to improve the skid properties of the pavement.

Acceptable and nonacceptable friction number ranges were obtained from the answers to questionnaire No.3 using the method described for the PSI. This information is summarized in Figures 4.5 to 4.7. Note that the same acceptable ranges were obtained for flexible and concrete pavements.

Screening of pavements

Pavement sections are first evaluated for roughness using the Roadmeter. The roadmeter reading of a section constitutes the input to the PSR-RR relationship which provides the PSI. Then, the PSI of the pavement section is compared with the acceptable serviceability range (ASR). This comparison is done using the "implication" operator (Watson et. al, 1979). This process evaluates the distance between the PSI and the ASR, i.e. how close the given fuzzy PSI is to the ASR. It can also be interpreted as the "truth value" for the implication that the PSI of a particular pavement section is acceptable. This truth value (μ_A) is called acceptability index and it takes values between 0.0 and 1.0. This index can be used to rank pavements according to their PSI. Since there may be pavements having the same fuzzy PSI and, thus, equal indices, a second index is calculated using the nonacceptable serviceability range (NASR). This is done by

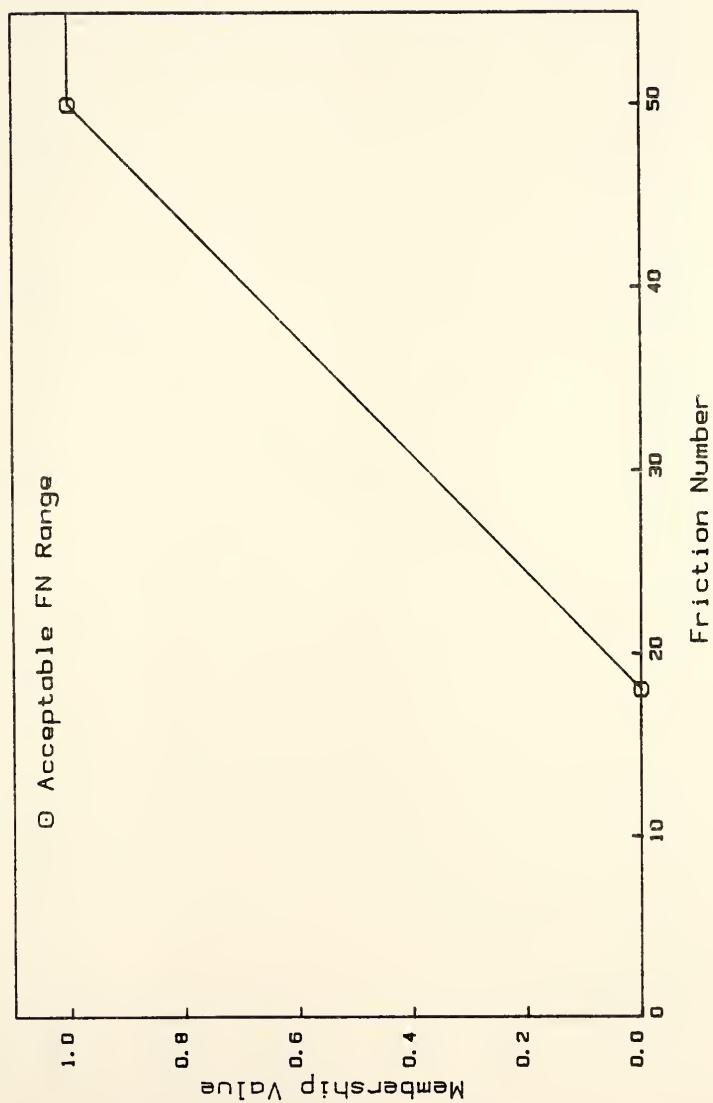


Figure 4.5. Acceptable Friction Number Range for Flexible and Concrete Pavements.

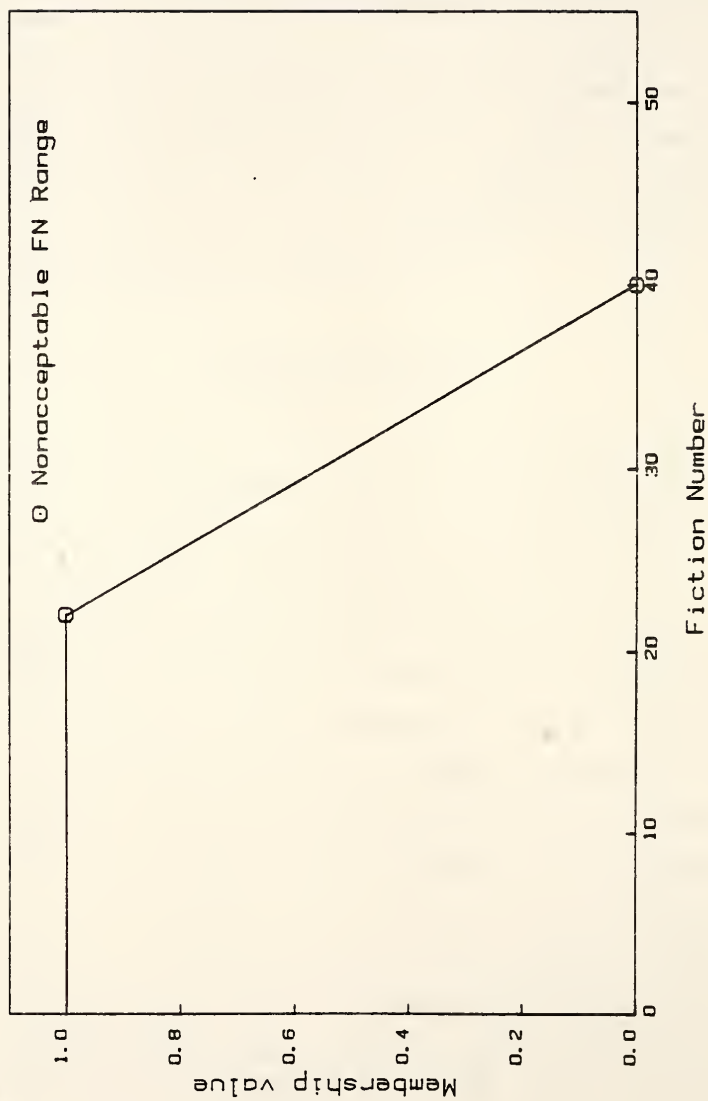


Figure 4.6. Nonacceptable Friction Number Range for Flexible Pavements.

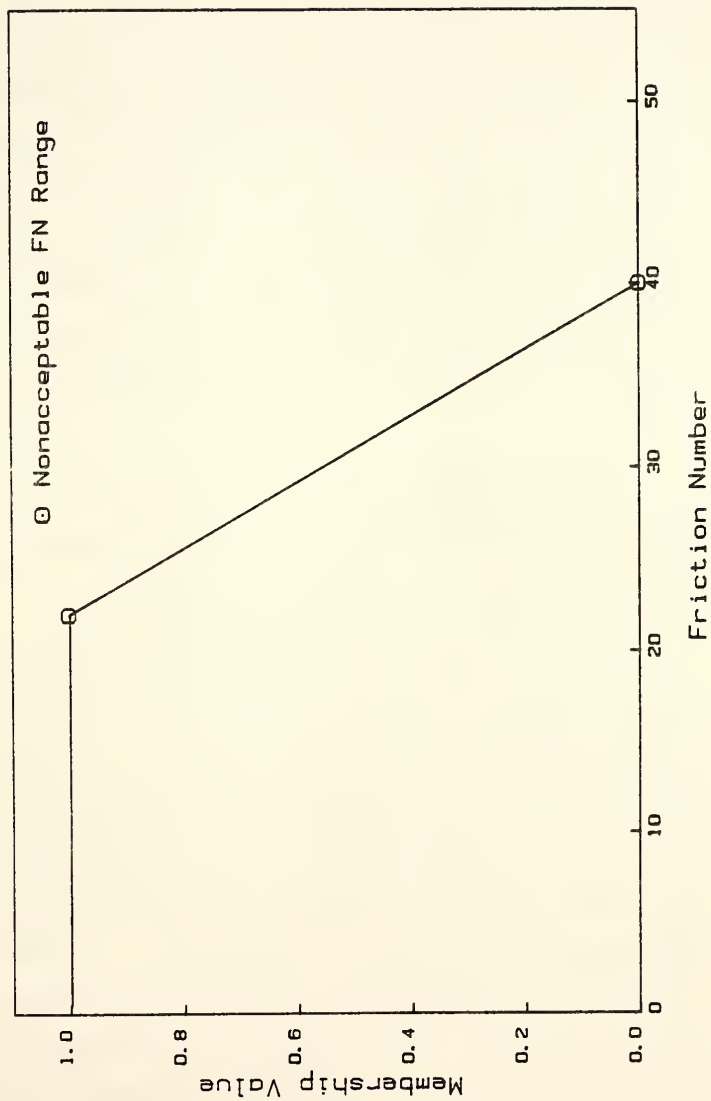


Figure 4.7. Nonacceptable Friction Number Range for Concrete Pavements.

evaluating the truth value for the implication that the PSI of a particular pavement section is nonacceptable. This truth value is denoted by μ_N and is called nonacceptability index, ranging also between 0.0 and 1.0.

The criterion used in this work for the initial screening is the following: if the fuzzy PSI of a given section is closer to the ASR than it is to the NASR (i.e., $\mu_A > \mu_N$), then the pavement is acceptable; in the opposite case, if the PSI is closer to the NASR than it is to the ASR (i.e., $\mu_N > \mu_A$), the pavement has nonacceptable roughness. The same techniques are applied when comparing friction numbers with acceptable or nonacceptable friction ranges.

Parametric studies were performed to show how the acceptability and nonacceptability indices vary as a function of RR and FN values. Indices were computed for RR values ranging from 0 to 3000 with increments of 100, and FN values from 0 to 100 with increments of 10. Plots of these indices versus RR and FN are given in Appendix D. These results were also used to evaluate how the techniques proposed to improve the PSR-RR relationship (chapter 1) affect the acceptability and nonacceptability indices. The study showed that these techniques result in smooth relationships between the indices and the RR and FN values (Appendix D).

Application

The initial screening of the pavement sections included in the data base given in chapter 3 was performed in several steps. The PSI values of the sections were obtained using the RR data and the PSR-RR relationship (See for example the RR values and corresponding fuzzy PSI for asphalt sections given in Appendix E). These PSI values were compared to the acceptable and nonacceptable PSI ranges to obtain the corresponding acceptability and nonacceptability indices. These indices were then used to classify the pavements with respect to roughness according to the procedure presented in the previous section. The results are summarized in Tables 4.1 to 4.4. They show the following: 5 out of 10 asphalt sections had acceptable roughness; all the overlay pavements and CRCP sections included in this study had acceptable roughness; 21 out of 28 JRC sections had acceptable roughness.

Friction Numbers of the pavement sections included in the data base (chapter 3) were fuzzified using the techniques described in chapter 2 (Typical results are given in Appendix E for the FN of asphalt sections). The comparison of the fuzzy FN with the acceptable and nonacceptable levels led to the results shown in Tables 4.5 to 4.8. All the asphalt sections considered had acceptable skid resistance. Only 2 out of 30 overlay pavements, 2 out of 28 JRC sections and one out of 13 CRCP sections considered had nonacceptable skid resistance. It is realized that almost all of the pavement sections considered had acceptable skid resistance. This is mainly because the pavements which

Table 4.1. RR Screening Results for Asphalt Sections.

<u>Section</u>	<u>RR</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	1669	0.038	0.070	Nonacceptable
2	895	0.430	0.0	Acceptable
3	794	0.510	0.0	Acceptable
4	1783	0.0	0.178	Nonacceptable
5	1661	0.037	0.070	Nonacceptable
6	1661	0.037	0.070	Nonacceptable
7	756	0.510	0.0	Acceptable
8	756	0.510	0.0	Acceptable
9	1417	0.075	0.008	Acceptable
10	1590	0.034	0.07	Nonacceptable

Table 4.2. RR Screening Results for Overlay Sections.

<u>Section</u>	<u>RR</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	1202	0.280	0.0	Acceptable
2	1707	0.130	0.120	Acceptable
3	1193	0.280	0.0	Acceptable
4	697	0.660	0.0	Acceptable
5	660	0.660	0.0	Acceptable
6	660	0.660	0.0	Acceptable
7	660	0.660	0.0	Acceptable
8	1118	0.280	0.0	Acceptable
9	1467	0.280	0.0	Acceptable
10	1133	0.288	0.0	Acceptable
11	1119	0.280	0.0	Acceptable
12	598	0.730	0.0	Acceptable
13	1397	0.280	0.0	Acceptable
14	678	0.660	0.0	Acceptable
15	971	0.398	0.0	Acceptable
16	1512	0.280	0.0	Acceptable
17	718	0.660	0.0	Acceptable
18	718	0.660	0.0	Acceptable
19	718	0.660	0.0	Acceptable
20	718	0.660	0.0	Acceptable
21	718	0.660	0.0	Acceptable
22	1685	0.130	0.119	Acceptable
23	1136	0.291	0.0	Acceptable
24	1136	0.291	0.0	Acceptable
25	1136	0.291	0.0	Acceptable
26	1489	0.280	0.0	Acceptable
27	1489	0.280	0.0	Acceptable
28	1113	0.280	0.0	Acceptable
29	1312	0.280	0.0	Acceptable
30	996	0.394	0.0	Acceptable

Table 4.3. RR Screening results for JRCP sections.

<u>Section</u>	<u>RR</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	2004	0.130	0.018	Acceptable
2	2190	0.101	0.070	Acceptable
3	2565	0.0	0.310	Nonacceptable
4	2430	0.045	0.190	Nonacceptable
5	1611	0.200	0.0	Acceptable
6	1510	0.215	0.0	Acceptable
7	1642	0.200	0.0	Acceptable
8	1707	0.200	0.0	Acceptable
9	1472	0.220	0.0	Acceptable
10	1467	0.221	0.0	Acceptable
11	1300	0.350	0.0	Acceptable
12	1585	0.237	0.0	Acceptable
13	1923	0.139	0.0	Acceptable
14	1727	0.183	0.0	Acceptable
15	2159	0.095	0.070	Acceptable
16	3045	0.0	1.000	Nonacceptable
17	2219	0.050	0.108	Nonacceptable
18	1869	0.130	0.0	Acceptable
19	1787	0.200	0.0	Acceptable
20	1417	0.280	0.0	Acceptable
21	2045	0.130	0.019	Acceptable
22	2141	0.092	0.070	Acceptable
23	2150	0.093	0.070	Acceptable
24	2715	0.0	0.550	Nonacceptable
25	2627	0.0	0.430	Nonacceptable
26	1994	0.130	0.017	Acceptable
27	2535	0.0	0.310	Nonacceptable
28	2133	0.090	0.070	Acceptable

Table 4.4. RR Screening Results for CRCP Sections.

<u>Section</u>	<u>RR</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	1663	0.350	0.0	Acceptable
2	1653	0.350	0.0	Acceptable
3	1501	0.430	0.0	Acceptable
4	1504	0.430	0.0	Acceptable
5	1854	0.209	0.0	Acceptable
6	1764	0.280	0.0	Acceptable
7	1097	0.660	0.0	Acceptable
8	1586	0.350	0.0	Acceptable
9	1324	0.551	0.0	Acceptable
10	1096	0.660	0.0	Acceptable
11	1715	0.280	0.0	Acceptable
12	1192	0.602	0.0	Acceptable
13	1379	0.510	0.0	Acceptable

Table 4.5. FN Screening Results for Asphalt Sections.

<u>Section</u>	<u>FN</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	63.8	1.0	0.002	Acceptable
2	37.0	0.55	0.120	Acceptable
3	57.0	1.0	0.0	Acceptable
4	42.5	0.710	0.059	Acceptable
5	42.5	0.710	0.059	Acceptable
6	42.5	0.710	0.059	Acceptable
7	52.0	0.977	0.0	Acceptable
8	52.0	0.977	0.0	Acceptable
9	41.3	0.680	0.021	Acceptable
10	40.9	0.680	0.002	Acceptable

Table 4.6. FN Screening Results for Overlay Sections.

<u>Section</u>	<u>FN</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	44.600	0.780	0.038	Acceptable
2	44.300	0.780	0.021	Acceptable
3	55.000	1.000	0.0	Acceptable
4	38.000	0.580	0.060	Acceptable
5	56.900	1.000	0.002	Acceptable
6	56.900	1.000	0.002	Acceptable
7	--	--	--	
8	46.400	0.840	0.038	Acceptable
9	46.400	0.840	0.038	Acceptable
10	43.100	0.740	0.002	Acceptable
11	42.600	0.710	0.038	Acceptable
12	55.000	1.000	0.0	Acceptable
13	29.700	0.310	0.540	Nonacceptable
14	53.900	1.000	0.002	Acceptable
15	46.100	0.810	0.002	Acceptable
16	--	--	--	
17	48.700	0.910	0.021	Acceptable
18	48.700	0.910	0.021	Acceptable
19	48.700	0.910	0.021	Acceptable
20	48.700	0.910	0.021	Acceptable
21	48.700	0.910	0.021	Acceptable
22	36.500	0.550	0.120	Acceptable
23	38.300	0.580	0.060	Acceptable
24	38.300	0.580	0.060	Acceptable
25	38.300	0.580	0.060	Acceptable
26	--	--	--	
27	--	--	--	
28	58.800	1.000	0.010	Acceptable
29	36.400	0.550	0.120	Acceptable
30	30.000	0.350	0.534	Nonacceptable

Table 4.7. FN Screening Results for JRCP Sections.

<u>Section</u>	<u>FN</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	37.2	0.580	0.008	Acceptable
2	36.0	0.510	0.150	Acceptable
3	31.7	0.380	0.400	Nonacceptable
4	32.4	0.410	0.340	Acceptable
5	38.6	0.610	0.059	Acceptable
6	41.7	0.710	0.038	Acceptable
7	41.2	0.680	0.010	Acceptable
8	42.0	0.710	0.0	Acceptable
9	41.5	0.710	0.086	Acceptable
10	46.4	0.840	0.038	Acceptable
11	32.4	0.410	0.034	Acceptable
12	--	--	--	
13	--	--	--	
14	36.0	0.510	0.150	Acceptable
15	37.0	0.550	0.080	Acceptable
16	36.9	0.550	0.080	Acceptable
17	36.1	0.534	0.150	Acceptable
18	33.7	0.450	0.270	Acceptable
19	37.4	0.580	0.080	Acceptable
20	40.0	0.680	0.0	Acceptable
21	38.3	0.610	0.038	Acceptable
22	37.6	0.580	0.059	Acceptable
23	37.2	0.580	0.080	Acceptable
24	38.4	0.610	0.059	Acceptable
25	40.3	0.640	0.038	Acceptable
26	31.1	0.380	0.460	Nonacceptable
27	39.3	0.640	0.038	Acceptable
28	40.3	0.640	0.038	Acceptable

Table 4.8. FN Screening Results for CRCP Sections.

<u>Section</u>	<u>FN</u>	<u>Accep. Index</u>	<u>Nonaccep. Index</u>	
1	9.90	0.059	1.0	Nonacceptable
2	42.7	0.740	0.038	Acceptable
3	42.7	0.740	0.038	Acceptable
4	41.9	0.710	0.002	Acceptable
5	41.3	0.680	0.038	Acceptable
6	43.4	0.740	0.059	Acceptable
7	39.5	0.640	0.086	Acceptable
8	36.7	0.550	0.080	Acceptable
9	41.1	0.680	0.002	Acceptable
10	44.1	0.780	0.002	Acceptable
11	40.0	0.680	0.0	Acceptable
12	40.4	0.658	0.059	Acceptable
13	36.4	0.550	0.150	Acceptable

become hazardous with respect to skid resistance are repaired immediately and a separate ranking for their maintenance priorities is not used at present.

According to the initial screening technique for PSI and FN, three categories of pavements are identified (Table 4.9). The first category includes the pavements with traffic hazards due to inadequate skid resistance. The second category contains the pavements with nonacceptable roughness, and the third category has the pavement sections with acceptable roughness and skid resistance. Table 4.10 shows how the pavement sections included in the data base (chapter 3) are distributed between the three categories. According to the initial screening results: 2 overlay, 2 JRCP and one CRCP sections had nonacceptable skid resistance and, thus, were included in category 1; 5 asphalt and 6 JRCP sections had nonacceptable roughness, falling in category 2; 5 asphalt, 28 overlay, 20 JRCP and 12 CRCP sections had acceptable roughness and skid resistance (category 3).

Summary

In this chapter, the acceptable and nonacceptable ranges for PSI and FN were developed using expert opinion. Initial screening of the pavement sections included in the data base was performed. The PSI is obtained using the PSR-RR relationship and is compared to the acceptable and nonacceptable ranges to define the acceptability of the pavement with regard to roughness.

Table 4.9. Primary Categorization of Pavements.

FIRST CATEGORY		SECOND CATEGORY		THIRD CATEGORY	
PSI	OK	PSI	No	PSI	OK
Friction Number	No	Friction Number	N/A	Friction Number	OK

Table 4.10. Primary Categorization of Pavement Sections
Included in the Data Base.

Category	Pavement Type			
	Asphalt	Overlay	JRC	CRC
1		13, 30	3, 26	1
2	1, 4, 5, 6, 10		4, 16, 17, 24, 25, 27	
3	2, 3, 7, 8, 9	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29,	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 18, 19, 20, 21, 22, 23, 28	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13

Note: Each number in the table corresponds to a pavement section
provided in the data base.

Similarly the FN is compared to the acceptable and nonacceptable ranges. Depending on which range the FN is closer to, the pavement is classified as having acceptable or nonacceptable friction number. It should be noted that once acceptable and nonacceptable serviceability and friction number ranges are established, they become part of the knowledge base. Therefore, future use of the system only requires that RR and FN values of the pavement section be known prior to initial screening.

CHAPTER 5

DECISION MAKING 2: PRIORITY ASSIGNMENT

The following step in the decision making process, after the initial screening of the pavement sections, is to rank sections in categories 1 and 2 for maintenance and rehabilitation. The pavements in the third category may also be ranked according to their remaining serviceability and friction lives.

The procedure developed by Gunaratne (1984) to rank pavement sections follows a multi-attribute decision making scheme. Similarly to the initial screening technique, this procedure requires expert knowledge before it can be implemented. This chapter shows how this expert knowledge base can be obtained and incorporated in the mathematical framework. Then, the ranking technique is illustrated using the pavement data given in chapter 3 and the results of the initial screening (chapter 4).

Attributes for immediate maintenance

A number of attributes were suggested in the study by Gunaratne (1984) to prioritize pavements in categories 1 and 2. The Friction Number (FN), Average Daily Traffic data (ADT) and the relative cost were selected for category 1. Dynaflect

measurements, ADT and PCR were proposed for category 2.

In this study, questionnaires were developed and submitted to experts to seek information regarding the relative importance of these attributes. The experts were asked to indicate a priority (utility) value on a specified scale which best describes the rehabilitation urgency of a pavement that has a given set of attribute values. They had to provide this information for a number of such sets covering a wide range of attribute values. Heuristic rules, adopted after years of pavement management experience, influence these subjective values provided by the experts. The priority for rehabilitation of defective pavement sections may vary from one expert to another. Furthermore, even an individual expert may be uncertain about the utility that he allocates. This is why the experts were asked to provide not only a utility value but also a range related to it for each set of attribute values being considered.

The reason for seeking this information is to be able to calculate a utility value for any combination of the attributes taken into consideration, and to evaluate the relative urgency of maintenance for a number of pavement sections. Note that the selected attributes are not necessarily the ones that the IDOH would decide to use in actual implementation of a fully developed ranking procedure. Hence, questions were asked to assess the experts' judgement on the relevance of these attributes. This has already led to changes in the attributes (next section) for both categories. In addition, suggestions were made for future

selection of attributes during an implementation program.

First category

Discussions with engineers from the Research and Training Center indicated that the PCR should be included as an attribute for pavements in the first category. The pavement condition rating is thought to provide an overall indication about the pavement's condition and, thus, should be included in any pavement ranking scheme for maintenance urgency. Furthermore, it was considered that the relative cost of repair was, in essence, a function of the performance data, FN and PCR. Therefore, there were only three independent attributes to be considered in the analysis: ADT, FN and PCR. Note that this is a convenient simplification which may need re-evaluation before actual implementation.

Questionnaire No.61 (Appendix A) included questions regarding the range of priority values for different combinations of attribute values. Highway experts were asked to provide priority values for combinations of attribute values such as ADT=8000, FN=20, and PCR=60, or ADT=6000, FN=30, and PCR=80. Nineteen responses were obtained from the experts. Twelve of them were in agreement with the suggested set of attributes (ADT, FN, PCR). The other 7 experts preferred a set of attributes containing only ADT and FN which was also included in questionnaire No.61. A number of other attributes were recommended by some of the experts:

- a) Percentage of trucks, types of trucks.
- b) Rate of deterioration of skid resistance.
- c) Maintenance history of the section.
- d) Accident history of the section.
- e) Roughness.
- f) Geometric considerations (turn lanes, width).
- g) Road use (i.e. coal-mine traffic).

These recommendations indicate that future implementation will require that a consensus on a desired set of attributes be reached among decision makers in the highway department. In this study the (ADT, FN, PCR) set of attributes was used to rank pavement sections in category 1, since more experts were in favor of this particular combination of attributes.

An interpolation method (Gunaratne, 1984) was used to build the knowledge base (expert system) from the responses obtained to the questionnaire No.61. These responses provide utility values for combinations of attribute values. These combinations cover the whole spectrum of attribute values but their number is limited. Hence, a point by point polynomial interpolation is necessary to obtain utilities for any other combination of attribute values. Conceptually, this method also implies that the utility function assigned by an expert should vary continuously with respect to each attribute.

The knowledge base is used to determine a fuzzy utility for each of the pavement sections to be ranked. This is accomplished through the interpolation function which gives the utility corresponding to the set of characteristics of any given section (i.e., ADT, FN and PCR). The fuzzy utility incorporates both the uncertainty in the characteristics of the section and in the expert information (knowledge base). The utility values of all the sections are then compared to identify the section which requires maintenance first. The process is repeated until all the sections are listed by order of maintenance urgency. The computer program "Dm.f" was developed to form the utility functions using the information provided by the experts, to obtain the fuzzy utility for any combination of attribute values, and to evaluate the relative rank with respect to maintenance urgency for any number of pavement sections.

Second category

Deflection data, ADT, PCR and relative cost were included as attributes to prioritize the pavement sections with nonacceptable roughness. Since deflection measurements are not conducted for the whole pavement system in Indiana, it was suggested by highway engineers to replace deflection with PSI in the set of attributes. The relative cost was assumed to be a function of the performance data, PSI and PCR, and, thus, only three independent attributes remained: ADT, PSI and PCR. Again, this simplification

may need re-evaluation before actual implementation.

Questionnaire No.611 included questions regarding priority values for a number of different combinations of those attribute values. The responses to questionnaire No.611 obtained from the 19 experts are summarized in Appendix A. Thirteen of these experts accepted the proposed set of attributes (ADT, PCR, PSI) for ranking unacceptably rough pavements. Ten of them considered that the (ADT, PCR, deflection) set of attributes was also a suitable set. The additional attributes suggested for ranking pavements in the first category were also proposed for this category.

The knowledge base for this category was obtained using the interpolation technique already used for category 1. The computer program "Dm.f" was also used to perform the ranking of pavement sections in the second category.

Typical application for sections in categories 1 and 2

The fuzzy PSI and FN of each pavement section included in the data base (chapter 3) were developed as explained in the previous chapters (chapters 1, 2, 4). The initial screening performed in chapter 4 resulted in the categorization of pavement sections in categories 1 and 2. In order to rank the pavement sections in these categories, their PCR's had to be obtained. This was accomplished using the method described in chapter 2 and the PCR data included in the data base (chapter 3). As an

example, the fuzzy PCR's of the unacceptably rough asphalt pavement sections are included in Appendix E. The computer program "Dm.f" was used to obtain the relative maintenance priorities of the pavement sections. The results obtained for each type of pavement are presented in the following:

Asphalt pavements

According to the results of the primary categorization (chapter 4), 5 out of 10 sections were in the second (nonacceptable roughness) and 5 in the third (acceptable roughness and skid resistance) categories.

The ranking of the 5 pavement sections in the second category is shown in Table 5.1. Three of the sections have exactly the same relative priority. This is explained by the fact that the PSI values of these sections were relatively close to each other. The relative priority of the last pavement is null as a result of the high value of its PCR (91).

Overlay pavements

Data from 30 pavement sections were analyzed. Two of them had nonacceptable skid resistance, falling in the first category. All of them had acceptable roughness. Therefore, two overlay pavement sections were ranked in category 1 (Table 5.2). The similarity in the condition of the two pavements explains why those two sections have close priorities.

JRCP sections

Data from 28 pavement sections were analyzed. Two of them had nonacceptable skid resistance and they were included in the first category of pavements. Six sections had nonacceptable roughness and were included in the second category. Twenty JRCP sections had acceptable roughness and skid resistance.

The ranking obtained for JRCP pavements in the first two categories is summarized in Tables 5.3 and 5.4. The higher ADT and the lower PCR of pavement section No.26 resulted in a higher relative priority as compared with section No.3 (Table 5.9). The results obtained for the pavements in category 2 suggest that maintenance priority can often be selected for groups of pavement sections, such as groups made of pavement sections 24 and 27, and sections 16 and 4.

CRCP sections

Data from 13 pavement sections were analyzed. All of them except one (No.1) had both acceptable skid resistance and roughness. Therefore, all these CRCP sections except one fell in the third category and, thus, will be ranked for future maintenance.

Attributes for future maintenance

Pavement sections in the third category satisfy rideability and skid resistance criteria at the time evaluation is being performed. Thus, they do not require any immediate maintenance. But

Table 5.1. Ranking of Asphalt Sections. Nonacceptable Roughness.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PCR</u>	<u>ADT</u>	<u>Rel. Priority</u>
6	1661	2.3	81	2406	0.294
5	1661	2.3	79	1600	0.294
4	1783	2.1	78	3209	0.294
1	1669	2.3	87	1313	0.235
10	1590	2.3	91	14500	0.000

Note: All of the RR, PSI and PCR values presented are the central values of the corresponding fuzzy sets.

Table 5.2. Ranking of Overlay Sections. Nonacceptable Skid Resistance.

<u>Section</u>	<u>FN</u>	<u>PCR</u>	<u>ADT</u>	<u>Rel. Priority</u>
13	28.7	91	6350	0.278
30	30.0	89	15387	0.222

Note: All of the RR, PSI and PCR values presented are the central values of the corresponding fuzzy sets.

Table 5.3. Ranking of JRCP Sections. Nonacceptable Skid Resistance.

<u>Section</u>	<u>FN</u>	<u>PCR</u>	<u>ADT</u>	<u>Rel. Priority</u>
26	31.1	71	9525	0.278
3	31.7	86	6450	0.193

Note: All of the RR, PSI and PCR values presented are the central values of the corresponding fuzzy sets.

Table 5.4. Ranking of JRCP Sections. Nonacceptable Roughness.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PCR</u>	<u>ADT</u>	<u>Rel. Priority</u>
24	2715	1.9	80	7312	0.353
27	2535	2.1	59	9525	0.353
25	2627	2.0	69	7312	0.325
16	3045	1.7	76	5500	0.294
4	2430	2.2	85	6450	0.294
17	2219	2.3	84	5500	0.250

Note: All of the RR, PSI and PCR values presented are the central values of the corresponding fuzzy sets.

their serviceability and skid resistance will deteriorate with time and ultimately will reach the terminal (nonacceptable) serviceability or friction level. Hence, these have to be considered for future rehabilitation. Prioritization for future rehabilitation is done using the serviceability and friction lives.

Expert opinion was sought by means of Questionnaire No.7 in which experts were asked to give a priority value range for the (PSI life, FN life) pair of attributes. The responses to questionnaire No.7, given by the 19 experts are included in Appendix A. Thirteen of them agreed with the proposed set of attributes. The other 6 experts suggested the addition of ADT as an attribute for the ranking of pavement falling in this category. Nevertheless, ADT was not considered as an attribute in this study since it is included in the determination of the remaining PSI and FN lives.

Determination of PSI Life

The most common method used in transportation engineering to determine the PSI life of a pavement is the AASHO method. Traffic load applied on the pavement, structural geometry of the pavement, and present serviceability are the most important factors being considered. The initial PSI is assumed to be 4.5 for rigid pavements, and the general AASHO Road Test equation for rigid pavements is:

$$\log \frac{4.5 - P_t}{4.5 - 1.5} = \beta * (\log W_{t_{18}} - \log \rho) \quad (5.1)$$

where P_t is the PSI value at time t , $W_{t_{18}}$ is the accumulated Equivalent Standard Axial Load (ESAL) up to time t , and SN is the Structural Number of the pavement. The parameters β and ρ are related to SN (for ESAL of 18 kip) by:

$$\beta = 1.0 + \frac{1.624 * 10^7}{(SN + 1)^{8.46}} \quad (5.2)$$

$$\text{and } \log \rho = 7.35 * \log (SN + 1) - 0.06 \quad (5.3)$$

Equations are also available for flexible pavements (AASHTO Interim Guide, 1972).

The Structural Number is a measure of the comparative strength of the pavement. SN is equal to the thickness of the slab for rigid pavements and is expressed as follows for flexible pavements:

$$SN = a_1 D_1 + a_2 D_2 + \dots + a_n D_n \quad (5.4)$$

where

a_1, a_2, \dots, a_n = Layer equivalency factors

D_1, D_2, \dots, D_n = Thickness of the individual pavement layers (surface, binder, base, etc.).

Overlay pavements were considered as acting like rigid pavements for this analysis since the strength of the overlay is small compared to the strength of the slab. It was assumed that the overlay restored the concrete pavement to its original condition and the SN was taken as the thickness of the original concrete slab.

A method to calculate the projected ESAL was proposed by Yoder and Witczak (1975). Knowing the percentage of trucks on the road and the factor that converts a truck-load to an 18 kips single axle load, i.e. the ESAL per truck, the following equation is used to obtain W_{t18} :

$$W_{t18} = 365 * \int_0^t ESAL_o * (1+i)^T * dT \quad (5.5)$$

$$ESAL_o = ADT_o * \% \text{ Trucks} * \text{ESAL per truck} \quad (5.6)$$

where $ESAL_o$ is the initial equivalent axle load application per day and i is the annual traffic growth. The percentage of trucks is obtained from either traffic counts or available past data information. The main drawback related to this method is the large amount of data required for each pavement section, namely:

- Determination of the structural number which requires the thickness of the surface, base and subbase.

- Determination of the projected ESAL (W_{t18}) which requires the percentage of trucks on the road and the factor that converts truck-load to 18 kip single axle load (ESAL per truck).

Data related to the above parameters were provided by the IDOH Research and Training Center and included in the data base given in chapter 3 (Tables 3.1 to 3.4). Information on the Structural Number and percentage of trucks was only available for pavement sections of the Interstate network. The value suggested for the ESAL per truck was 0.6949 (obtained from an IDOH Division of Planning Publication: Traffic Statistics-1981). The values for percentage of trucks were also provided by the same source. An average traffic growth factor of 4% per year was used.

The time to reach the terminal performance level is the service life of a pavement with respect to a particular pavement property. Therefore pavement serviceability life is equal to the time needed for the PSI to reach the Nonacceptable Serviceability Range (NASR). Since both the PSI and the NASR are represented by fuzzy sets, it follows that the pavement serviceability life will also be a fuzzy quantity because of the nature of the input variables. The program "pslife.f" was developed to find the pavement serviceability performance vs. time relationship for each pavement section using the AASHO method and to evaluate the fuzzy PSI life using the mathematical techniques developed by Gunaratne

(1984). As a typical example, the fuzzy PSI life for overlay section No.29 is shown in Figure 5.1. The results obtained with this program for the pavements in the data set are summarized in Tables 5.5 to 5.7. The central values of the fuzzy PSI lives of the pavement sections considered in the four categories vary from 4.2 years, corresponding to a present PSI of 2.8, to 15.1 years, for a present PSI of 3.1.

Determination of Friction Life

Research conducted by the Research and Training Center of the IDOH (1982) has produced regression equations to predict the friction number of a pavement as a function of time:

Asphalt pavements:

$$FN = 152.5 - 16.522 * XL + a_1 * SPI - b_1 * SUI \quad (5.7)$$

Overlay pavements (equation corresponding to highest correlation coefficient):

$$FN = 165.3 - 19.220 * XL + a_2 * SPI - b_2 * SUI \quad (5.8)$$

Concrete pavements:

$$FN = 116.6 - 10.250 * XL + a_3 * SPI + b_3 * SUI \quad (5.9)$$

In these equations:

$$XL = \log_{10} \left(\sum_{n=0}^{n=t} ADT \right) * 365 \quad (5.10)$$

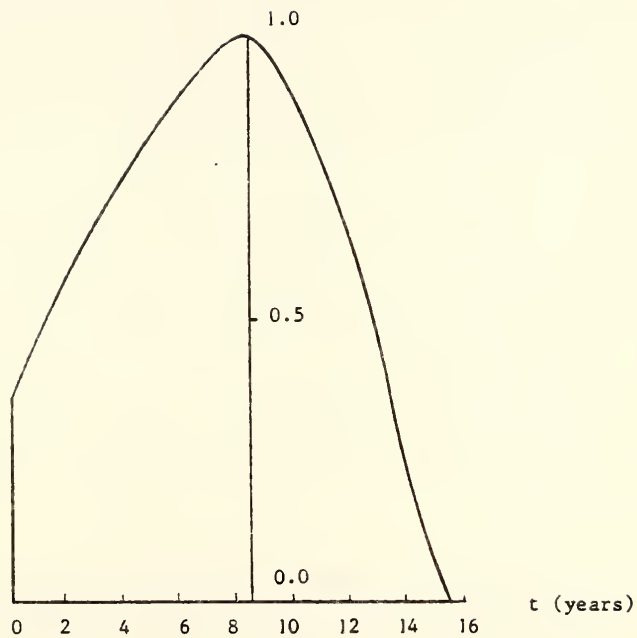


Figure 5.1. Typical Fuzzy PSI Life.

$$\sum_{n=0}^{n=t} ADT = [ADT_0 + ADT_0(1+i) + ADT_0(1+i)^2 + \dots + ADT_0(1+i)^n] \quad (5.11)$$

where

SPI = spring factor

SUI = summer factor

SPI is equal to 1.0 if measurements are made in the spring and 0.0 otherwise. Similarly SUI is equal to 1.0 if measurements are made in the summer and 0.0 otherwise.

Seasonal variations of the FN of a pavement section were not considered here since they were incorporated as imprecision in the friction measurements due to changes in temperature and rainfall. Furthermore, the friction life of a pavement is related to the non-recoverable reduction in skid resistance and, thus, all the coefficients a_1 , a_2 , a_3 , b_1 , b_2 and b_3 are null in equation 5.9.

The program "flife.f" was written to develop the skid resistance performance vs. time relationship for each section using the above equations. The fuzzy FN Life was evaluated using the performance relation, the FN of the section and the nonacceptable FN range.

The results obtained for the analyzed data set are given in Tables 5.6 to 5.8. As a typical example, the fuzzy friction life for overlay section No.29 is shown in Figure 5.2. All of the pavement sections included in the analysis have central friction

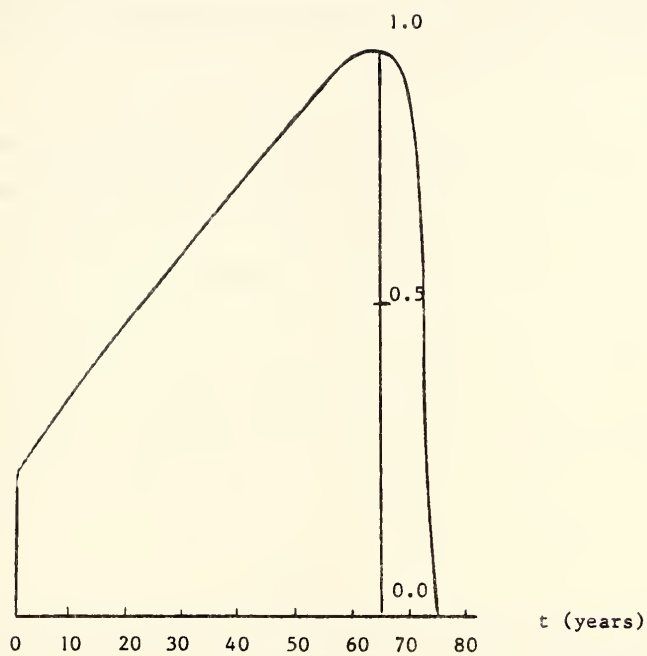


Figure 5.2. Typical Fuzzy FN Life.

lives varying from 40 to 90 years. This is mainly because pavements that have low skid resistance are repaired immediately. Therefore, it is very likely that the friction number of the pavement sections included in this study represent the situation of the section after at least one repair. This implies that the measured FN does not represent the deterioration of the section since it was constructed.

High friction lives of 40 years and above imply that this particular attribute will not affect the ranking of these pavements for future maintenance. Hence, the pavements falling in the third category (acceptable roughness and skid resistance) were ranked with respect to PSI life only. The ranking of the pavements was performed by ordering the pavement sections from the lowest to the highest remaining serviceability life using the central values. The results are given in Tables 5.8 to 5.10.

Summary

In this chapter the knowledge base required to rank the pavement sections within the three different categories was formed using the responses to questionnaires. The pavement sections provided in the data set (chapter 3) were ranked for maintenance urgency or future performance using the proposed techniques. The number of pavement sections in categories 1 and 2 was limited for this particular data set, but the technique can be applied to any number of pavement sections for which performance and traffic characteristics are available. Future

implementation of the proposed methodology may include different or more attributes in the ranking procedure.

Table 5.5. PSI Life and Friction Life For Overlay Pavement Sections.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PSI Life</u>	<u>FN</u>	<u>FN Life</u>
28	1113	2.9	8.9	59.0	86
29	1312	2.7	8.5	36.0	64

Note: All of the RR, PSI, PSI Life, FN and FN Life values presented are the central values of the corresponding fuzzy sets.

Table 5.6. PSI Life and Friction Life for JRCP Sections.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PSI Life</u>	<u>FN</u>	<u>FN Life</u>
1	2004	2.5	7.1	37.2	74
2	2190	2.4	6.1	36.0	72
5	1611	2.8	4.2	38.6	61
6	1510	2.9	4.6	41.7	66
7	1642	2.8	9.2	41.2	83
8	1707	2.8	10.3	42.0	96
9	1472	2.9	11.8	41.5	91
11	1300	3.1	15.1	32.4	46
14	1727	2.7	9.2	36.0	72
15	2159	2.4	6.3	37.0	78
18	1869	2.6	8.4	33.7	61
19	1787	2.7	9.2	37.4	72
20	1417	3.0	9.2	40.0	67
21	2045	2.5	6.1	38.3	73
22	2141	2.4	5.3	37.6	72
23	2150	2.4	5.2	37.2	70
28	2133	2.4	5.3	40.3	78

Note: All of the RR, PSI, PSI Life, FN and FN Life values presented are the central values of the corresponding fuzzy sets.

Table 5.7. PSI Life and Friction Life for CRCP Sections.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PSI Life</u>	<u>FN</u>	<u>FN Life</u>
2	1653	2.8	10.5	42.7	82
3	1501	2.9	11.6	42.7	81
4	1504	2.9	11.5	41.9	82
5	1854	2.6	8.2	41.3	78
6	1764	2.7	8.8	43.4	75
7	1097	3.3	14.5	39.5	64
8	1586	2.8	8.3	36.7	58
9	1324	3.1	11.1	41.1	66
10	1096	3.3	13.1	44.1	57
11	1715	2.7	7.4	40.0	66
12	1192	3.2	13.3	40.4	66
13	1379	3.0	9.5	36.4	60

Note: All of the RR, PSI, PSI Life, FN and FN Life values presented are the central values of the corresponding fuzzy sets.

Table 5.8. Ranking of Overlay Sections.
Acceptable Roughness and Skid Resistance.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PSI Life</u>	<u>FN</u>	<u>FN Life</u>	<u>Rel. Priority</u>
29	1312	2.7	8.5	36.0	64	1
28	1113	2.9	8.9	59.0	86	2

Notes:- All of the RR, PSI, PSI Life, FN and FN Life values presented are the central values of the corresponding fuzzy sets.

- The Relative Priority is obtained using the PSI Life only.

Table 5.9. Ranking of JRCP Sections.
Acceptable Roughness and Skid Resistance.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PSI Life</u>	<u>FN</u>	<u>FN Life</u>	<u>Rel.</u>	<u>Priority</u>
5	1611	2.8	4.2	38.6	61		1
6	1510	2.9	4.6	41.7	66		2
23	2150	2.4	5.2	37.2	70		3
22	2141	2.4	5.3	37.6	72		4
28	2133	2.4	5.3	40.3	78		4
2	2190	2.4	6.1	36.0	72		5
21	2045	2.5	6.1	38.3	73		5
15	2159	2.4	6.3	37.0	78		6
1	2004	2.5	7.1	37.2	74		7
18	1869	2.6	8.4	33.7	61		8
7	1642	2.8	9.2	41.2	83		9
14	1727	2.7	9.2	36.0	72		9
19	1787	2.7	9.2	37.4	72		9
20	1417	3.0	9.2	40.0	67		9
8	1707	2.8	10.3	42.0	96		10
9	1472	2.9	11.8	41.5	91		11
11	1300	3.1	15.1	32.4	46		12

Notes:- All of the RR, PSI, PSI Life, FN and FN Life values presented are the central values of the corresponding fuzzy sets.

- The Relative Priority is obtained using the PSI Life only.

Table 5.10. Ranking of CRCP Sections.
Acceptable Roughness and Skid Resistance.

<u>Section</u>	<u>RR</u>	<u>PSI</u>	<u>PSI Life</u>	<u>FN</u>	<u>FN Life</u>	<u>Rel.</u>	<u>Priority</u>
11	1715	2.7	7.4	40.0	66		1
5	1854	2.6	8.2	41.3	78		2
8	1586	2.8	8.3	36.7	58		3
6	1764	2.7	8.8	43.4	75		4
13	1379	3.0	9.5	36.4	60		5
2	1653	2.8	10.5	42.7	82		6
9	1324	3.1	11.1	41.1	66		7
4	1504	2.9	11.5	41.9	82		8
3	1501	2.9	11.6	42.7	81		9
10	1096	3.3	13.1	44.1	57		10
12	1192	3.2	13.3	40.4	66		11
7	1097	3.3	14.5	39.5	64		12

Notes:- All of the RR, PSI, PSI Life, FN and FN Life values
presented are the central values of the corresponding
fuzzy sets.

- The Relative Priority is obtained using the PSI Life only.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Summary

This report followed the framework proposed by Gunaratne (1984) for the development of an improved pavement evaluation and management system. Emphasis was given to the development of the knowledge base (expert information) required by this system. Application of the techniques used in this decision making system was demonstrated for a typical data set supplied by the IDOH Research and Training Center.

Knowledge base

The knowledge base consists of the following elements:

a) Variation in parameters: The measured RR values were represented by fuzzy sets. Variations due to irrepeatability, climatic and vehicle speed changes were modeled by attaching a range of variation to the measured RR number.

Friction numbers of the pavement sections were also expressed as fuzzy sets. Climatic and vehicle speed changes were modeled by introducing ranges of variation.

At present, the IDOH does not use Deflection numbers at any stage of the decision making for prioritizing the pavements. This parameter is only used as undersealing criterion. Therefore, there was not enough deflection data available to include this parameter in the evaluation as was proposed by Gunaratne (1984).

Fuzzy sets were introduced in distress surveys, since human based uncertainty affects evaluation of the different kinds of distress.

b) PSR-RR relationship: The PSR-RR relationship (matrix) was formed using the data supplied by the IDOH Research and Training Center. This data was related to a limited number of pavement sections and was not sufficient to completely determine the PSR-RR matrix. Two alternate techniques were developed to overcome this problem.

c) Acceptable levels for PSI and FN: Acceptable serviceability and skid resistance levels were obtained from the responses provided by experts. Since there is no clear demarcation line between acceptability and nonacceptability levels, a transition zone was used in this study as guided by the experts' responses.

d) Utility Values: Utility values were provided by experts for a number of selected combinations of attribute values, covering a wide range of those attributes. This was done for each of the three categories of pavements. Using this information and a point by point polynomial interpolation, the corresponding fuzzy utilities can be obtained for any combination of attribute

values. These attributes were: Friction Number, Pavement Condition Rating, and Average Daily Traffic for pavements in the first category (nonacceptable skid resistance); Pavement Serviceability Index, Pavement Condition Rating, and Average Daily Traffic (ADT) for pavements in the second category (nonacceptable roughness); and PSI and Friction Lives as attributes for the pavements in the third category.

Application of the method

The first step in the proposed method is to gather the following data: Annual Daily Traffic, Roadmeter Reading, and Friction Number for the pavement sections that are going to be ranked. The Pavement Condition Rating is not necessary for pavement sections that have acceptable roughness and skid resistance according to the results of the initial screening.

The next step is to fuzzify the RR and FN using the ranges provided by the experts. Then, the PSR-RR knowledge base is entered with the fuzzy RR, and the fuzzy PSI is obtained. The PSI and FN are compared with acceptable and nonacceptable levels and the initial screening of the pavements is performed. PCR values are obtained for pavements with nonacceptable roughness and the corresponding fuzzy sets are created. Finally, the pavement sections are ranked with respect to urgency for maintenance, using the utility functions which contain the knowledge base provided by experts. The computer programs necessary for the different stages of the method were developed (Appendix F). The input

required from the user consists of performance and traffic data such as RR, FN, PCR and ADT. A typical example of application was given using the data set provided by the IDOH. This particular data set contained a limited number of sections for each pavement type.

The knowledge base required to use the method is formed once. It consists of the PSR-RR relationship, acceptability and nonacceptability levels for PSI and FN, and utility values for a given number of combinations of the attributes affecting the performance of the pavements. The knowledge base can be updated at any time when new data become available.

Conclusions

The use of the new fuzzy sets based methodology for pavement evaluation and maintenance has been demonstrated in this report. The following conclusions can be drawn from the results of this work:

- 1) The formulation of the fuzzy sets techniques to handle subjectivity and uncertainty has been successful. The techniques generate crisp rankings of pavement sections for maintenance urgency.

- 2) The existing pavement management system contains fewer decision criteria than can be handled by the fuzzy sets techniques. This is acknowledged by some experts, by their suggestions to include more variables as, e.g. traffic classification

data, especially heavier trucks. Any desired criteria for which a consensus exists among the experts can be included in future implementation.

3) The existing data base available for the Indiana road system can not take full advantage of the proposed pavement management system. There are gaps in the data, whose presence was discovered by the manipulations during the study. The developed ranking method will be utilized more effectively if a PCR inventory for pavement sections with nonacceptable roughness becomes available.

4) The knowledge base that has been created can be used to rank any number of pavement sections. The only effort needed is to obtain the relevant performance and traffic data for the pavement sections that need to be ranked.

CHAPTER 7

RECOMMENDATIONS

The following recommendations are suggested for future implementation of the proposed techniques:

a) More responses should be obtained for the questionnaires seeking information about the ranges of variation pertinent to the performance parameters, i.e. Roadmeter Reading, Friction Number, Pavement Condition Rating, etc.

b) Sufficient data points must be used to develop the PSR-RR knowledge base. This can be accomplished by using a panel of raters who will rate a larger number of pavements covering the whole range of roughness, that is, pavements with very poor to very good riding quality.

c) The roadmeter must be recalibrated periodically against the raters' opinions. Therefore new panel ratings should be frequently obtained.

d) Other attributes such as percentage of trucks, accident and maintenance history of the pavement, and rate of deterioration of skid resistance, can be included in the decision making

scheme. Expert opinion need to be obtained for different combinations of these attributes.

e) Linguistic terms such as "many accidents" and "high rate of deterioration of skid resistance", can be represented by fuzzy sets if any of the above additional attributes are included in the pavement ranking procedure. Additional information related to the quantification of the linguistic terms should be obtained from the experts.

f) All the computer programs used for the application of the proposed techniques can be modified to be used on a personal computer. In addition, they can be combined into a single program that will use the stored knowledge base, and the input traffic and performance data of the pavement sections in order to evaluate their ranking with respect to maintenance urgency.

BIBLIOGRAPHY

BIBLIOGRAPHY

- AASHO, "AASHO Interim Guide for the Design of Pavement Structures - 1972", Washington, D.C., 1972.
- Bellman R.E, and Zadeh L.A, "Decision-making in a Fuzzy Environment", Management Science, Vol. 17, pp. B141-B164, Dec. 1970
- Blockley, D.I., "Analysis of Structural Failures", Proc. of the Institution of Civil Engineers, 1(62), pp. 51-79, 1977.
- Blockley, D.I., "The Role of Fuzzy Sets in Civil Engineering", Fuzzy Sets and Systems 2, North-Holland Publishing Company, pp. 267-278, 1979.
- Brown, C.B. and Yao, J.T.P., "Fuzzy Sets and Structural Engineering", ASCE Journal of Structural Engineering, Vol. 109, No. 5, May 1983
- Chameau, J.L., Altschaeffl, A.G., Michael, H.L. and Yao, J.T.P., "Potential Applications of Fuzzy Sets in Civil Engineering", Jour. of Man-Machine Studies, Vol. 19, 1983.
- Chameau, J.L. and Gunaratne, M., "Performance Evaluation in Geotechnical Engineering Using Fuzzy Sets," Proceedings of the ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability, Berkeley, California, 1984.
- Chameau, J.L., Gunaratne, M. and Altschaeffl, A.G., "Type 2 Fuzzy Sets in Engineering", Proceedings of the First International Conference on Fuzzy Information Processing, Kauai, Hawaiian Islands, 1984.
- Dubois, D. and Prade, H., "Fuzzy Sets and Systems: Theory and Applications", Academic Press, New York, 1980.
- Gunaratne, M., "The Use of Fuzzy Sets Mathematics in Pavement Evaluation and Management", Draft Interim Report, FHWA/IN/JHRP-84/18, Purdue University, 1984.
- Gunaratne, M., Chameau, J.L., and Altschaeffl, A.G., "An Introduction to Fuzzy Sets in Pavement Evaluation", presented at the Transportation Research Board Annual Meeting, Washington, D.C., January 1984, to be published in the Transportation Research Board Records.

- Gupta, M.M., Saridis, G.N. and Gaines, B.R., "Fuzzy Automata and Decision Processes", Elsevier North-Holland, 1977.
- IDOH, "Traffic Statistics-1981", Prepared by Division of Planning IDOH, October 1982.
- IDOH, "1983 Summary of Pavement Roughness", IDOH Research and Training Center, 1983.
- IDOH, "1983 Summary of Pavement Friction", IDOH Research and Training Center, 1983.
- Kercher, K., "Personal Communication", Indiana Department of Highways, Research and Training Center, October 1984.
- Louie, D. H., "Fuzzy Sets and Their Applications to Civil Engineering Safety Measures", Master of Science in Civil Engineering, Univ. of Washington, Seattle, 1981.
- Metwali, E.W., "Framework for a Pavement Evaluation System", Joint Highway Research Project Report, JHRP-81-7, Purdue University, 1981.
- Mizumoto, M. and Tanaka, K., "Some Properties of Fuzzy Sets of Type 2," Information and Control, Vol. 31, 1976.
- Mohan, S., "Development of a System for the Evaluation of Pavements in Indiana", Interim Report, Joint Highway Research Project, JHRP-78-21, Purdue University, 1978.
- Nakamura, V.F., and Michael, H.L., "Serviceability Ratings of Highway Pavements", Highway Research Record, Highway Research Board, No. 40, pp. 21-36, 1963.
- Partridge, B., "Personal Communication", Indiana Department of Highways, Research and Training Center, September 9, 1982.
- Research and Training Center(IDOH), "Optimizing Indiana Pavement Surfaces", Final report, FHWA/IN/RTC-82/1, Indiana department of highways, September 1982.
- Saaty, T.L., "A Scaling Method for Priorities in Hierarchical Structures", Journal of Mathematical Psychology, 15, 1977.
- Shimura, M., "Fuzzy Sets Concepts in Rank-Ordering Objects", Journal of Mathematical Analysis and Applications, Vol. 43, 1973.
- Shiraishi, N., and Furuta, H., "Reliability Analysis Based on Fuzzy Probability", Journal of Engineering Mechanics, ASCE, Vol. 109, No. 6, December 1983.

- Transportation Research Board, "Pavement Management", Transportation Research Record No. 846, Transportation Research Board, National Research Council, 1982.
- Transportation Research Board, "Evaluation of Pavement Maintenance Strategies", National Cooperative Highway Research Program, Synthesis of Highway Practice, 56 pp., Report No. 77, 1981.
- Transportation Research Board, "Collection and Use of Pavement Condition Data", NCHRP, Syn. of Highway Practice, Report No. 76, ISBN 0-309- 03161-3, 74pp., 1981.
- Yao, J.T.P., "Damage Assessment of Existing Structures", Journal of the Engineering Mechanics Division, ASCE, pp. 785-799, Vol. 106, August 1980.
- Yao, J.T.P., Fu, K.S. and Ishizuka, M., "Fuzzy Statistics and its Potential Applications in Civil Engineering", ASCE Convention, St. Louis, 1981.
- Yoder, E.J., "Development of a System for the Evaluation of Pavements in Indiana", Joint Highway Research Project, JHRP-81-8, Purdue University, 1981.
- Yoder, E.J. and Witczak M.W., "Principles of Pavement Design", John Wiley & Sons, Inc., Second Edition, 1975.
- Yoder, E.J. and Milhous, R.T., "Comparison of Different Methods of Measuring Pavement Condition", NCHRP Report 7, 1964.
- Zadeh, L.A., "Fuzzy Sets", Information and Control, Vol. 8, 1965.
- Zadeh, L.A., "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes," IEEE Trans. Syst. Man. Cybern. Vol. SMC - 3, No. 1, January 1973.
- Zadeh, L.A., "Probability Measures of Fuzzy Events", Journal of Mathematical Analysis and Applications, 23, pp. 421-427, 1968.
- Zadeh, L.A., "Fuzzy Logic and Its Application to Approximate Reasoning", Information Processing 74, 1974.
- Zadeh, L.A., "Fuzzy Sets as a Basis for a Theory of Possibility", International Journal of Fuzzy Sets and Systems, No. 1, pp. 3-28, 1978.
- Zadeh, L.A., "Making Computers Think like People", IEEE Spectrum, pp. 26-32, August 1984.

APPENDICES

APPENDIX A

Appendix AQuestionnaires and responses

Questionnaire No. 1

The initial screening of road sections in determining needs for major maintenance is road roughness as measured by the roadmeters. Roughness data are calibrated (or correlated) with data from road rating panels in which a variety of road users cast their respective subjective judgment about the "quality" of the different pavement sections.

In the past, data from rating panels were lumped and no distinction was made between responses from different people. It has been suggested that raters with different backgrounds and experience will view pavement condition in different ways. This is consequent to the fact that urgency of maintenance, to some extent, depends on the likelihood that the pavement surface conditions suggest "serious" internal problems, that the conditions represent "serious" traffic hazards and whether the difficulties warrant correction in light of traffic volumes carried by the section. Each rater, then, has a different perspective towards the question of pavement "quality", and our objective is to gather highway experts' subjective opinions about raters' perceptiveness on pavement serviceability.

Thus, we seek your judgment. We have prepared a series of questions to allow us to assemble your judgment with those of

others regarding the relative weight to be assigned to individual ratings, when road sections' Present Serviceability Ratings (PSR) are being established.

1. Do you agree that judgments of some raters could deserve more weight when assembling panel data, depending on their perceptiveness of the serviceability question?

Yes No

2. If different weights are to be attached to the judgments, basically it is convenient to group them according to their backgrounds so that a single weight could be attached to each group. Table 1 describes the professional backgrounds and the ages of one such rating panel. One possible grouping for this panel is presented in Table 2. Do you agree with this grouping?

Yes No

If your response is "No" please proceed to Q.7.

IF YOU AGREE WITH THE BASIC GROUPING.

3. If judgments of different raters deserve different relative weightings, on a scale of 00 to 2.0 what such levels would you assign to each group in determining Pavement Serviceability Ratings from this panel? (Assign a value such as 0.5 or 1.1 or 1.5 depending on the subjective perceptiveness you place on each group's judgment).

Group	Relative weight
-------	-----------------

A

B

C

OR

Do you believe that each group's judgment should be viewed exactly the same in obtaining the PSR?

Yes	No
-----	----

4. After the basic grouping do you agree that categorization according to experience and other factors within a group is appropriate as shown in Table 2?

Yes	No
-----	----

5. If the answer to Question 4 is "Yes", now we seek your subjective opinion on relative weighting factors to be assigned for the judgments of the respective sub-groups (taken as a unit) in a scale of 0.0-1.0?

Sub Group	Weighting Factor
-----------	------------------

Minor

Major

6. If the answer to Question 4 is "No" then do you wish to see some changes between minor and major subgroups?

Yes No

If "Yes" please indicate them on Table 2. (Indicate the rater to be shifted to the other sub-group by placing a "*" in front of him.) Further, what relative weighting factors would you assign for your modified sub-groups (each considered as a unit)

Sub-Group	Factor
-----------	--------

Minor

Major

OR

Do you have other suggestions for categorization within a group?

Yes No

If "Yes" please indicate them on the provided sheet.

Please proceed to Question No. 20.

IF YOU DISAGREE WITH THE BASIC GROUPING

7. Do you feel that a reassembly should be performed keeping the main groups the same?

Yes No

If the response is "No" please proceed to Question No. 13.

8. If the answer to Question 7 is "Yes" please indicate on Table 2 which rater you would shift and to where shifted. (Indicate this by writing the new group name in front of the rater.)
9. With your modified groups, please indicate your suggested relative weighting levels in the same manner as per instructions in Question 3. Use the table below to record your responses.

Group	Relative Weight
A	
B	
C	

10. Do you agree with the idea of categorizing within a group according to experience (age) if they are of the same professional types or according to their interest in pavements if they are of different background?

Yes	No
-----	----

11. If the answer to Question 10 is "Yes" indicate the distribution of raters you would use for major and minor sub-groups for each of your groups. (Indicate this by writing M - for Major or m - for minor in front of the raters you have shifted in Table A2.)

12. For your sub-groups (each considered as a unit), on a scale of 0.0 - 1.0, what relative weighting levels would you attach to each?

Sub-group

Weighting Factor

Major

Minor

Please proceed to Question No. 20.

13. If the answer to Question 7 was "No", are you of the opinion that more main groups should be formed according to their backgrounds?

Yes No

14. If the answer to Question 13 is "Yes" please indicate main groups you would propose [Indicate the group name in front of each rater in Table A1.]

With your newly formed groups please answer Question 15, 16, 17 and 18 as per instructions in Questions 9, 10, 11 and 12, respectively.

15.

Group

Relative
Weight

A

B

C

D

E

16. Yes No

17. Use Table 1 for your responses.

18. Sub-group Weighting Factor

Major

Minor

*19. If the response to Question 1 was "No" please indicate why not on the sheet provided.

FINALLY

20. A list of Highway users with various backgrounds who could be members of serviceability rating panels in general, is shown in Table A3 along with their ages. Please indicate in the space provided, on a scale of 0.0-2.0 the relative weights you would place in each raters judgment, in your subjective opinion.

Results obtained from questionnaire No.1

Table A1. List of a Rating Panel.

Let us assume we have a rating panel of 16 people. Listed below are their stated job titles and ages.

1	Highway Research Engineer	(20-29)
2	Training Officer (Administrative)	(40-49)
3	Highway Research Engineer	(30-39)
4	"	(50-59)
5	"	(20-29)
6	Engineering Asst. Supervisor	(30-39)
7	Mechanic	(30-39)
8	Secretary	(30-39)
9	Highway Research Engineer	(50-59)
10	Highway Engineering Assistant	(20-29)
11	"	(20-29)
12	Electronics Technician	(40-49)
13	Bituminous Laboratory Technician	(20-29)
14	Highway Engineering Assistant	(30-39)
15	"	(20-29)
16	"	(50-59)

Table A2 . A Grouped Rating Panel.

A Group			B Group		C Group	
	Profession	Age	Profession	Age	Profession	Age
Major	Research Eng.	50-59	Engineering Asst.	50-59	Lab. Technician	20-29
	Research Eng.	50-59	Eng. Asst. Super.	30-39	Mechanic	30-39
					Electronics Technician	40-49
Minor	Research Eng.	30-39	Eng. Assistant	30-39	Training Off.	40-49
	Research Eng.	20-29	Eng. Assistant	20-29	Secretary	30-39
	Research Eng.	20-29	Eng. Assistant	20-29		
			Eng. Assistant	20-29		

Table A3. Weights for the Opinion of Highway Users Who Could be Called to Serve on Rating Panels.

First line in each category are experts under 40 years old.

Second line in each category are experts over 40 years old.

Profession:

a. Highway Research Engineer	1.6	1.0	1.25	1.8	2.0	1.8	1.9	1.75	1.2—>1.59
	1.7	1.2	1.75	1.9	2.0	1.9	2.0	2.0	1.2—>1.74
b. Civil Engineers associated with highways	1.8	1.4	1.75	1.7	2.0	1.9	1.9	1.5	1.2—>1.68
	2.0	1.2	2.0	1.8	2.0	2.0	2.0	1.75	1.2—>1.77
c. Other Civil Engineers	1.5	0.8	1.0	1.5	1.9	1.4	1.7	1.0	1.2—>1.33
	1.6	0.8	1.5	1.6	1.9	1.5	1.8	1.0	1.2—>1.43
d. Mechanical Engineers	1.4	0.8	1.0	1.4	1.8	1.2	1.1	1.0	1.0—>1.19
	1.5	0.8	1.25	1.4	1.8	1.3	1.2	1.0	1.0—>1.25
e. Other Engineers	1.4	0.8	1.0	1.4	1.8	1.2	1.1	1.0	1.0—>1.19
	1.5	0.8	1.25	1.4	1.8	1.3	1.2	1.0	1.0—>1.25
f. Engineering Assistants associated with highways	1.5	1.0	1.25	1.4	1.2	1.6	1.4	1.0	1.0—>1.26
	1.6	0.9	1.5	1.5	1.2	1.7	1.5	1.25	1.0—>1.35
g. Other Civil Engineering assistants	1.4	0.9	1.0	1.4	1.1	1.1	1.3	0.75	1.0—>1.11
	1.5	0.9	1.0	1.5	1.1	1.2	1.4	1.0	1.0—>1.18
h. Non-Civil Engineering assistants	1.2	0.75	0.75	1.2	1.0	0.9	0.9	0.5	0.8—>0.89
	1.3	0.75	0.75	1.2	1.0	1.0	1.0	0.75	0.9—>0.96
i. Civil Engineering laboratory technicians	1.4	0.8	0.75	1.2	1.0	0.9	1.1	0.5	1.0—>0.96
	1.5	0.7	0.75	1.3	1.0	1.0	1.2	0.75	1.0—>1.02
j. Non-Civil Engineering technicians	1.2	0.9	0.75	1.2	1.0	0.8	0.9	0.4	0.8—>0.88
	1.3	0.7	0.75	1.2	1.0	0.9	1.0	0.5	0.8—>0.91
k. Truck Driver	1.5	1.0	1.0	1.3	1.0	0.5	1.3	0.4	0.8—>0.98
	1.6	1.0	1.25	1.3	1.0	0.6	1.4	0.5	0.8—>1.05
l. Highway Research Administrator	1.6	1.2	1.5	1.4	2.0	1.5	1.9	2.0	1.2—>1.59
	1.7	1.4	1.75	1.5	2.0	1.6	2.0	2.0	1.2—>1.68
m. Other Professionals	1.4	1.0	1.25	1.3	1.3	0.9	0.9	0.5	1.0—>1.07
	1.5	0.9	1.25	1.3	1.3	1.0	1.0	0.5	1.0—>1.09
n. Working road users	1.0	0.9	0.75	1.2	1.0	0.5	1.3	0.4	0.8—>0.87
	1.2	0.9	1.0	1.3	1.0	0.6	1.4	0.5	0.8—>0.97
o. Housewives	1.0	0.75	0.5	0.9	1.0	0.4	0.6	0.25	0.8—>0.69
	1.2	0.75	0.75	1.0	1.0	0.5	0.7	0.3	0.8—>0.78

Table A4. Weights for Grouping (1.0-2.0).

	<u>A</u>	<u>B</u>	<u>C</u>
	1.3	1.3	1.05
	1.2	1.0	0.8
	1.5	1.0	0.5
	1.2	1.0	0.8
	1.5	1.0	0.5
	2.0	1.0	0.5
	2.0	1.5	0.75
	2.0	1.5	0.5
	1.8	1.5	1.1
	1.5	1.1	1.0
	2.0	1.2	1.0
	-----	-----	-----
Av.	1.636	1.191	0.773
S.Dev.	0.333	0.221	0.242

Table A5. Weights for Subgrouping.

	<u>W1</u>	<u>W2</u>
	0.5	0.5
	0.5	0.5
	0.5	1.0
	1.0	1.2
	---	---
	0.2	0.8
	0.75	1.0
	0.5	1.0
	0.65	0.9
	0.5	0.5
	-----	-----
Average	0.567	0.822
St.Dev.	0.219	0.264
Normalized	0.408	0.592

Questionnaire No. 2

Our previous questionnaire addressed the formation of a pavement serviceability rating (PSR), which incorporates the different degrees of perceptiveness of different raters.

Our next objectives are to correlate our PSR with roadmeter reading, obtain the PSI for pavement sections and to compare the PSI with the acceptable serviceability index (ASI) in rank-ordering pavements according to rideability.

In this questionnaire we seek your judgment on the inherent variability of the roadmeter and on the acceptable serviceability indices. These will allow us to develop a complete PSI model, while including all of the previous provisions for different degrees of perceptiveness and human uncertainty.

1. The Indiana Department of Highways, and also many other highway departments compare performances of pavements and set maintenance priorities based on the pavement serviceability index (PSI), as derived from the correlation of the roadmeter reading and the pavement serviceability rating (PSR). PSI takes values on a scale of 0.0-5.0. The PSI history of a pavement section shows that deterioration of the pavement quality occurs with time, leading to a sharp decrease in PSI below which the pavement condition becomes a traffic hazard. This hazardous stage is not sharply defined, and different people will recognize it at slightly different stages as their perceptions of the cost of

rehabilitation and the dangers involved with such a pavement differ.

a) Above what value of PSI, in your opinion, is a primary (major) pavement totally acceptable for traffic? (This is the Acceptable Serviceability Index or ASI.) Please answer the same question for a secondary pavement.

<u>Type of Pavement</u>	<u>ASI</u>
Primary	
Secondary	

b) Below what PSI value in your opinion is a primary pavement totally inadequate? (This is the Non-acceptable Serviceability Index or NASI.) Please answer the same question for a secondary pavement.

<u>Type of Pavement</u>	<u>NASI</u>
Primary	
Secondary	

2. Pavement Serviceability Rating is the combined judgment by the rating panel of the quality of the pavement. Each rater assigns a value for the section on the scale of 0.0-5.0 according to his or her perception of the serviceability of a pavement section. The rater's judgment is an imprecise number since if he or she is given more trials under similar conditions, repetitions of

the previous rating cannot be expected in general. In other words, since the judgment is purely subjective, he or she obviously gives considerable support to a domain around the assigned value. Therefore, it is believed that an individual opinion is better represented by such a range rather than a discrete number.

a) Do you agree with this idea?

b) If so, what in your opinion is the interval that such a rating can be within? [For example, if a rating of 2.5 can, in your opinion, be any value between 2.2 and 2.8, the required interval is 0.6.]

3. Inspection of roadmeter readings obtained from repeated trials on a given pavement section reveals a significant scatter. This may be mainly due to the inability of the roadmeter to replicate the same path every time it scans the contract section.

We can consider the roadmeter reading as supporting a range of values rather than a discrete value, in order to account for this imprecisely defined roughness.

Let us assume that the count obtained for a certain section is 500. If it is thought that a range of 10% of this count represents the variability of the reading, it may be appropriate to represent the roughness of that section by the interval 450-550, with the highest belief attached to 500.

a) Do you agree with this idea?

b) What such interval in your opinion is suitable to characterize a roadmeter reading? (Please provide the interval as a percentage of the reading.)

4. It is known that the gas tank level, driver characteristics and changes in air temperature have some influence on the roadmeter reading.

a) For a certain driver, assuming standard air temperature conditions (60 degrees F) , what is, in your opinion, the variability in roadmeter reading induced by the possible variations in the gas tank level. [Ex. For a roadmeter reading of 600, if the gas tank level changes vary the roadmeter reading within 594 and 606, then the required range is 2%.]

b) For a certain driver, assuming no changes in the gas tank level, in your opinion what range of variation is possible in the roadmeter reading due to any changes in air temperature from the standard value of 60 degrees F. Please respond according to the example in 4.a.

c) Assuming standard temperature conditions and that there are no gas tank level changes, in your opinion what range of values is possible for a certain roadmeter reading due to possible variations in driver characteristics (i.e., unsteadyness, etc.)? Please respond according to the example in 4.a.

Results obtained from questionnaire No.2

Note: Answers were provided by 7 experts. Each column in the following tables refers to the answer of an expert.

Table A6. ASI (Acceptable Serviceability Index)

Question 1a.

	<u>ASI</u>							<u>Mean</u>	<u>S.Dev.</u>
Primary	3.0	2.5	2.5	3.0	3.5	3.0	2.5	2.86	0.38
Secondary	2.5	2.0	2.0	3.0	2.5	2.5	1.5	2.29	0.49

Table A7. NASI (Nonacceptable Serviceability Index).

Question 1b.

	<u>NASI</u>							<u>Mean</u>	<u>S.Dev.</u>
Primary	2.0	2.0	2.0	2.25	2.5	2.0	2.0	2.11	0.20
Secondary	1.5	1.5	1.5	2.25	1.5	2.0	1.5	1.68	0.31

Table A8. Range of Variation for PSR.

								<u>Mean</u>	<u>S.Dev.</u>
Question 2a.	yes	yes	yes	yes	yes	yes	yes		
Question 2b.	0.5	0.5	0.5	0.6	0.4	0.4	0.6	0.50	0.08

Table A9. Range of Variation for RR Due to Irrepeatability.

							<u>Mean</u>	<u>S.Dev</u>
Question 3a.	yes	yes	yes	yes	no ex.	yes	yes	
Question 3b.	15%	---	7.5%	12.5%	---	5%	5%	9.0% 4.54

Table A10. Gas Tank Level Effect on RR Range.

								<u>Mean</u>	<u>S.Dev.</u>
				(*)					
Question 4a.	1.%	no ex.	2.0%	0.%	no ex.	no ex.	0.%	0.75%	0.96

Table A11. Air Temperature Effect on RR Range.

								<u>Mean</u>	<u>S.Dev.</u>
Question 4b.	0%	no ex.	1.5%	0.0%	no ex.	no ex.	6%	2.125	2.658

Table A12. Driver Characteristics Effect on RR Range.

								<u>Mean</u>	<u>S.Dev.</u>
Question 4c.	1.%	no ex.	2%	0.0%	no ex.	no ex.	10%	3.25	4.57

(*) No ex. indicates no experience.

Table A13. Acceptable Serviceability Range.

PRIMARY PAVEMENTS

Value

2.4	0/7=0.00
2.5	3/7=0.4286
2.6	3/7= "
2.7	3/7= "
2.8	3/7= "
2.9	3/7= "
3.0	6/7=0.8571
3.1	6/7= "
3.2	6/7= "
3.3	6/7= "
3.4	6/7= "
3.5	7/7=1.0000

SECONDARY PAVEMENTS

Value

1.4	0/7=0.00
1.5	1/7=0.1429
1.6	1/7= "
1.7	1/7= "
1.8	1/7= "
1.9	1/7= "
2.0	3/7=0.4286
2.1	3/7= "
2.2	3/7= "
2.3	3/7= "
2.4	3/7= "
2.5	6/7=0.8571
2.6	6/7= "
2.7	6/7= "
2.8	6/7= "
2.9	6/7= "
3.0	7/7=1.0000

Using linear regression
-----Primary

$$\frac{0.05}{2.2} + \frac{0.13}{2.3} + \frac{0.20}{2.4} + \frac{0.28}{2.5} + \frac{0.35}{2.6} + \frac{0.43}{2.7} + \frac{0.51}{2.8} + \frac{0.58}{2.9} + \frac{0.66}{3.0} +$$

$$\frac{0.73}{3.1} + \frac{0.81}{3.2} + \frac{0.88}{3.3} + \frac{0.96}{3.4} + \frac{1.00}{3.5}$$

Secondary

$$\frac{0.04}{1.5} + \frac{0.10}{1.6} + \frac{0.16}{1.7} + \frac{0.23}{1.8} + \frac{0.29}{1.9} + \frac{0.35}{2.0} + \frac{0.42}{2.1} + \frac{0.48}{2.2} + \frac{0.54}{2.3} +$$

$$\frac{0.61}{2.4} + \frac{0.67}{2.5} + \frac{0.73}{2.6} + \frac{0.80}{2.7} + \frac{0.86}{2.8} + \frac{0.92}{2.9} + \frac{0.99}{3.0} + \frac{1.00}{3.1}$$

Table A14. Nonacceptable Serviceability Range.

PRIMARY PAVEMENTS

Value

2.0	7/7=1.0000
2.1	2/7=0.2857
2.2	2/7=0.2857
2.3	2/7=0.2857
2.4	1/7=0.1429
2.5	1/7=0.1429
2.6	0/7=0.00

SECONDARY PAVEMENTS

Value

1.5	7/7=1.0000
1.6	2/7=0.2857
1.7	2/7=0.2857
1.8	2/7=0.2857
1.9	2/7=0.2857
2.0	2/7=0.2857
2.1	1/7=0.1429
2.2	1/7=0.1429
2.3	1/7=0.1429
2.4	0/7=0.0000

Using linear regression

Primary

$\frac{1.0}{1.7}$	$+$	$\frac{0.92}{1.8}$	$+$	$\frac{0.8}{1.9}$	$+$	$\frac{0.68}{2.0}$	$+$	$\frac{0.55}{2.1}$	$+$	$\frac{0.43}{2.2}$	$+$	$\frac{0.31}{2.3}$	$+$	$\frac{0.19}{2.4}$	$+$	$\frac{0.07}{2.5}$
-------------------	-----	--------------------	-----	-------------------	-----	--------------------	-----	--------------------	-----	--------------------	-----	--------------------	-----	--------------------	-----	--------------------

Secondary

$\frac{1.0}{0.9}$	$+$	$\frac{0.93}{1.0}$	$+$	$\frac{0.86}{1.1}$	$+$	$\frac{0.79}{1.2}$	$+$	$\frac{0.72}{1.3}$	$+$	$\frac{0.66}{1.4}$	$+$	$\frac{0.59}{1.5}$	$+$	$\frac{0.52}{1.6}$	$+$	$\frac{0.45}{1.7}$	$+$
$\frac{0.39}{1.8}$	$+$	$\frac{0.32}{1.9}$	$+$	$\frac{0.25}{2.0}$	$+$	$\frac{0.18}{2.1}$	$+$	$\frac{0.12}{2.2}$	$+$	$\frac{0.05}{2.3}$							

Questionnaire No. 3

Our previous questionnaires dealt with the determination of pavement serviceability rating (PSR) and acceptable serviceability index (ASI). These determinations include the use of the weights in data manipulations to account for different degrees of perceptiveness of different panel members rating a pavement. Uncertainty inherent in the roadmeter reading was also considered.

Now let us assume that pavement sections have been sorted out into those having acceptable or non-acceptable serviceability indices. For those having acceptable values, it is still possible that they require speedy maintenance to account for in-service behavior that it not included in the context of the PSR (rideability) concept.

For the pavements having acceptable serviceability indices, the next step in the evaluation system is categorization according to the level of skid-resistance. In the State of Indiana, skid-resistance of pavements is measured by the skid-tester and the friction number obtained is $100 \times$ the coefficient of friction and can be any value between 0 and 100.

The friction number is found to be influenced by a number of factors such as temperature, rainfall and the speed of the tester. The changes due to these factors are so irregular that even the current statistical methods have not succeeded in identifying

a systematic variation. In the presence of these variables, a precise friction number cannot be defined. Due to this lack of precision, the skid-resistance of a contract section leads to system uncertainty.

The purpose of this questionnaire is to gather subjective information from experts, regarding the friction number variability and the acceptable friction numbers to ensure safety of traffic.

1a. According to your judgment, above what friction number can the traffic move without significant risk of skidding? If you believe that this value depends on the pavement type, please indicate your values corresponding to each pavement type in the relevant spaces below.

Type of Pavement

FN

Asphalt

Overlay

CRCP

JRCP

1b. According to your judgment, below what friction number is resurfacing necessary to prevent skidding? Please fill the following table as per instructions in the above question.

Type of PavementFN

Asphalt

Overlay

CRCP

JRCP

2. Research on the skid-tester has revealed that the friction number of a pavement section is affected by the climatic conditions (temperature and rainfall differences) and, the speed of the skid-tester, which are independent of each other.

1) The friction number of a pavement section is obtained under given climatic conditions, defined by temperature and rainfall. If this number is to represent the skid characteristics of that section under any climatic condition (assuming that there are no vehicle speed changes), it may be more appropriate to indicate an interval instead of a unique number.

a) Do you agree with this idea?

If your response is "No" please proceed to 2(ii).

b) What such friction number interval should be specified for a certain friction number according to your judgment?

You may use the following table to indicate your answer, as a percentage of the friction number. [For example, if you believe that for a pavement indicating a friction number of 50,

the friction numbers due to possible climatic changes could be within 45 and 55, the required interval is 20%.]

<u>Pavement Type</u>	<u>Friction Number</u>
Asphalt	
Overlay	
CRCP	
JRCP	

ii) Suppose that the friction number of a pavement section is obtained for a given vehicle speed, which might be different from the standard vehicle speed. If that number is to account for any such speed changes from the standard vehicle speed (assuming that there are no climatic changes) it may be more appropriate to specify a friction number interval along with the above friction number.

a) Do you agree with this idea?

b) What such interval, in your opinion, should be specified for a certain friction number?

You may use the following table to indicate your answer, as per instructions in 2(i).

Pavement TypeFriction Number

Asphalt

Overlay

CRCP

JRCP

Results obtained from questionnaire No.3

Note: Answers were provided by 8 experts. Each column in the following tables refers to the answer of an expert.

Table A15. Acceptable Friction Number.

Question 1a.

<u>Type of pavement</u>	<u>FN</u>								<u>Mean</u>	<u>S.Dev.</u>
Asphalt	20	40	30-35	--	35	25-30	40	40	32.8	7.12
Overlay	20	40	30-35	--	35	25-30	40	40	32.8	7.12
CRCP	20	40	30-35	--	35	25-30	40	40	32.8	7.12
JRCP	20	40	30-35	--	35	25-30	40	40	32.8	7.12

(--) indicates that no answer was provided.

Table A16. Acceptable Friction Number Range.

Same responses obtained for both flexible and concrete pavements.

Value	
19	0/7
20	1/7
21	1/7
22	1/7
23	1/7
24	1/7
25	1/7
26	1/7
27	1/7
28	2/7
29	2/7
30	2/7
31	2/7
32	2/7
33	3/7
34	3/7
35	4/7
36	4/7
37	4/7
38	4/7
39	4/7
40	7/7

Using linear regression

$$\frac{0.02}{20} + \frac{0.05}{21} + \frac{0.08}{22} + \frac{0.12}{23} + \frac{0.15}{24} + \frac{0.18}{25} + \frac{0.22}{26} + \frac{0.25}{27} + \frac{0.28}{28} +$$

$$\frac{0.31}{29} + \frac{0.35}{30} + \frac{0.38}{31} + \frac{0.41}{32} + \frac{0.45}{33} + \frac{0.48}{34} + \frac{0.51}{35} + \frac{0.55}{36} + \frac{0.58}{37} +$$

$$\frac{0.61}{38} + \frac{0.64}{39} + \frac{0.68}{40} + \frac{0.71}{41} + \frac{0.74}{42} + \frac{0.78}{43} + \frac{0.81}{44} + \frac{0.84}{45} + \frac{0.88}{46} +$$

$$\frac{0.91}{47} + \frac{0.94}{48} + \frac{0.97}{49} + \frac{1.00}{50}$$

Table A17. Nonacceptable Friction Number.

Question 1b.

<u>Type of pavement</u>	<u>FN (below)</u>								<u>Mean</u>	<u>S.Dev.</u>
Asphalt	25	35	20-25	--	25	20-30	40	30	27.8	6.67
Overlay	25	35	20-25	--	25	20-30	35	30	27.2	5.65
CRCP	25	35	20-25	--	25	20-30	30	30	26.7	5.00
JRCP	25	35	20-25	--	25	20-30	30	30	26.7	5.00

(--) indicates that no answer was provided.

Table A18. Nonacceptable Friction Number Range.

Flexible Pavements		Concrete Pavements	
-----	-----	-----	-----
22	7/7	22	7/7
23	6/7	23	6/7
24	6/7	24	6/7
25	6/7	25	6/7
26	6/7	26	6/7
27	6/7	27	6/7
28	6/7	28	6/7
29	3/7	29	3/7
30	3/7	30	3/7
31	3/7	31	3/7
32	3/7	32	3/7
33	3/7	33	3/7
34	3/7	34	3/7
35	2/7	35	1/7
36	0/7	36	0/7

Using linear regression

Flexible Pavements

$$\begin{aligned}
 & \frac{1.00}{22} + \frac{0.96}{23} + \frac{0.90}{24} + \frac{0.84}{25} + \frac{0.78}{26} + \frac{0.72}{27} + \frac{0.66}{28} + \frac{0.60}{29} + \frac{0.54}{30} + \\
 & \frac{0.48}{31} + \frac{0.42}{32} + \frac{0.36}{33} + \frac{0.30}{34} + \frac{0.24}{35} + \frac{0.18}{36} + \frac{0.12}{37} + \frac{0.06}{38}
 \end{aligned}$$

Concrete Pavements

$$\begin{aligned}
 & \frac{1.00}{22} + \frac{0.97}{23} + \frac{0.91}{24} + \frac{0.84}{25} + \frac{0.78}{26} + \frac{0.72}{27} + \frac{0.65}{28} + \frac{0.59}{29} + \frac{0.53}{30} + \\
 & \frac{0.46}{31} + \frac{0.40}{32} + \frac{0.34}{33} + \frac{0.27}{34} + \frac{0.21}{35} + \frac{0.15}{36} + \frac{0.08}{37} + \frac{0.02}{38}
 \end{aligned}$$

Table A19. Range of Variation Due to Climatic Changes.

Question 2i.

<u>Type of pavement</u>		<u>FN</u>							<u>Mean</u>	<u>S.Dev.</u>
Asphalt	5%	--	20-30%	--	6%	no	20%	10%	13.0	10.6
Overlay	5%	--	20-30%	--	6%	no	20%	10%	13.0	10.6
CRCP	5%	--	20-30%	--	6%	no	10%	10%	11.6	10.2
JRCP	5%	--	20-30%	--	6%	no	10%	10%	11.6	10.2

Table A20. Range of variation Due to Vehicle Speed Changes.

Question 2ii.

<u>Type of pavement</u>		<u>FN</u>							<u>Mean</u>	<u>S.Dev.</u>
Asphalt	5%	--	no	--	no	no	no	yes	1.00	2.24
Overlay	5%	--	no	--	no	no	no	yes	1.00	2.24
CRCP	5%	--	no	--	no	no	no	yes	1.00	2.24
JRCP	5%	--	no	--	no	no	no	yes	1.00	2.24

(--) indicates that no answer was provided.

Questionnaire No. 4

Three questionnaires have been previously sent out by us with the objective of collecting highway engineers' expertise on pavement evaluation. Those questionnaires addressed the incorporation of the raters' perceptiveness in serviceability rating, acceptable serviceability indices, roadmeter variability and the variability associated with the friction number. Techniques are available to include this expert knowledge, once gathered, in the pavement evaluation system using fuzzy sets mathematics.

In assigning priorities for maintenance, pavement sections are first separated into two categories, with acceptable and unacceptable PSI values. The sections with acceptable roughness are then tested for skid-resistance and by means of an acceptable friction number they are further sub-divided into two categories: acceptable and unacceptable skid levels. Currently, the IDOH is planning to develop a procedure to test the sections with unacceptable roughness (PSI) for deflections in order to obtain overlay design thicknesses.

Indiana Department of Highways uses the dynaflect for deflection testing. Variability is also associated with the dynaflect reading which is vulnerable to changes in climatic conditions. Furthermore, the inability to repeat a reading at a particular test position also contributes to this.

In this questionnaire we address the problem of variability associated with the deflection reading. We seek your judgment on

the possible extent of these variations to enable us to incorporate them in the evaluation system.

1. Results of dynaflect tests at the same location on a given section reveals a wide scatter. Thus, it may be appropriate to characterize the deflection by a range of values. Assuming no climatic changes, in your opinion what range of variation would you expect in the dynaflect reading at the same location on repeated trials? [Ex.: If the dynaflect reading at a certain location is 8 mils and you believe that in repeated measurements it may lie between 7.6 and 8.4 mils, then the required range is 10%.]

Please indicate your answer as a percentage in front of each pavement type given below.

<u>Pavement Type</u>	<u>Possible range of variation (%)</u>
Asphalt	
Overlay	
CRCP	
JRCP	

2a. Deflections measured at the edge of a pavement are considered more critical because deterioration usually initiates at the edge. It is, however, more convenient to measure the center deflections, which are later correlated to the edge deflections. What factors would you propose to be used in converting center

deflections to those at the edge? Please indicate your answer corresponding to each pavement type.

<u>Pavement type</u>	<u>Edge def./center def.</u>
Asphalt	
Overlay	
CRCP	
JRCP	

Currently these factors are obtained by statistical methods. But we notice that the analysts' subjective judgment invariably is involved in such procedures. For example, when using the analysis of variance (ANOVA) method to get the conversion factors, only the "80th percentile" values of the variances of each set of deflections are considered. Imprecision is also introduced due to the difficulty in identifying the "edge", especially for deteriorated pavements, since the edge deflection is defined as that at a distance of 2' from the edge. Therefore, it is proposed that these factors be replaced by appropriate tolerance intervals in order to handle the above mentioned human and system uncertainties involved in the edge-center deflection correlation.

Do you agree with this idea?

b) If so, what tolerances should be attached to the above factors? Please indicate your answer as a percentage of the factor, in the following table. [Ex: If you think it is appropriate to use a factor of 2.0 for the ratio of edge

deflection/center deflection for flexible pavements, and when the above mentioned uncertainties are taken into account, if, in your opinion, this factor could be any value between 1.5 and 2.5 the required tolerance for flexible pavements is $\pm 25\%$.]

<u>Pavement Type</u>	<u>Tolerance (%)</u>
----------------------	----------------------

Asphalt	
---------	--

Overlay	
---------	--

CRCP	
------	--

JRCP	
------	--

3a. In Indiana, deflections measured during the spring thaw period are found to be the most critical for overlay design purposes. But in practice it is difficult to scan all the deteriorated pavement sections with the dynaflect within this short period. Thus, deflections are usually measured during Fall and later converted to the corresponding spring deflections. What factors would you suggest using for this conversion? Please indicate your answer corresponding to each pavement type.

<u>Pavement Type</u>	<u>Spring def./center def</u>
----------------------	-------------------------------

Asphalt	
---------	--

Overlay	
---------	--

CRCP	
------	--

JRCP	
------	--

These factors are presently obtained by statistical correlation procedures. But it is seen that for some pavement types the correlation coefficients are relatively low (i.e., in the order of 0.2, etc.). This scatter of data imparts imprecision on the factors so derived. Therefore, it seems more appropriate to replace these factors by suitable tolerance intervals.

Do you agree with this idea?

b) If so, in your opinion what tolerances should be attached to the above factors to make them more representative of the possible values. Please indicate your answer as a % of the factor in the following table. [Ex: If it is appropriate to use a factor of 1.5 for the ratio of spring deflection/fall deflection for asphalt pavements, and when the above mentioned imprecision inherent in deriving these factors is taken into account, if, according to your judgment, this factor could be any value between 1.35 and 1.65 the required tolerance for asphalt pavements is $\pm 10\%$.]

<u>Pavement Type</u>	<u>Tolerance (%)</u>
Asphalt	
Overlay	
CRCP	
JRCP	

Results obtained from questionnaire No.4

Note: Answers were provided by 7 experts. Each column in the following refers to the answer of an expert.

Table A21. Range of Variation for Dynaflect Reading at the Same Location on Repeated Trials, Assuming No Climatic Changes.

Question 1.

<u>Type of pavement</u>	<u>DR Variation (%)</u>						<u>Mean</u>	<u>S.Dev.</u>	
Asphalt	10	--	2-3	--	15	--	10	8.0	5.43
Overlay	10	--	2-3	--	15	--	10	8.0	5.43
CRCP	5	--	2-3	--	10	--	5	5.0	3.08
JRCP	5	--	2-3	--	12	--	5	5.4	3.91

Table A22. "Edge deflection/Center deflection" values.

Question 2a.

<u>Type of pavement</u>	<u>Edge def./Center def.</u>	<u>Mean</u>	<u>S.Dev.</u>
Asphalt			
Overlay			
CRCP	No answer was provided to Question 2a.		
JRCP			

(--) indicates that no answer was provided.

Table A23. Tolerance to be Attached to the Above Factors.

Question 2b.

<u>Type of pavement</u>		<u>Tolerance</u>								<u>Mean</u>	<u>S.Dev.</u>
Asphalt	±20%	--	--	--	--	--	--	--	--	±20.0	--
Overlay	±20%	--	--	--	--	--	--	--	--	±20.0	--
CRCP	±20%	--	--	--	--	--	--	--	--	±20.0	--
JRCP	±20%	--	--	--	--	--	--	--	--	±20.0	--

Table A24. Ratio of Spring Deflections/Fall Deflections.

Question 3a.

<u>Type of pavement</u>		<u>Spring def./Fall def.</u>								<u>Mean</u>	<u>S.Dev.</u>
Asphalt											
Overlay											
CRCP											
JRCP											

No answer was provided to Question 3a.

Table A25. Tolerance to be Attached to the Above Factors.

Question 3b.

<u>Type of pavement</u>		<u>Tolerance for Spring def./Fall def.</u>								<u>Mean</u>	<u>S.Dev.</u>
Asphalt	±20%	--	--	--	--	--	--	--	--	±20%	--
Overlay	±20%	--	--	--	--	--	--	--	--	±20%	--
CRCP	±20%	--	--	--	--	--	--	--	--	±20%	--
JRCP	±20%	--	--	--	--	--	--	--	--	±20%	--

(--) indicates that no answer was provided.

Questionnaire No. 5

We have previously sent four questionnaires which dealt with various stages of our research on application of fuzzy sets mathematics to pavement evaluation. They addressed the subjectivity involved in pavement serviceability rating, acceptable serviceability rating and in the variability associated with Roadmeter, Skid-tester and Dynaflect readings.

In the pavement management system, pavements are screened initially for serviceability at the network level, and each section is either of acceptable or unacceptable roughness.

The Indiana Department of Highways is creating a procedure for the content of distress surveys. A crew is to examine and roughly estimate the extent and severity of different pavement defects in a selected length of a section at a designated mile post. Separate instruction sheets have been prepared for flexible and rigid pavements to assist the crew in assigning ratings. The combined rating is known as the pavement condition rating (PCR). It is obvious that human based uncertainty enters the PCR by way of imprecision of measurements and subjective judgments. The purpose of this questionnaire is to seek your expertise on the magnitude of the above mentioned uncertainties for various kinds of distresses, as well as the acceptable level of distress for different types of pavements.

1. It is proposed that pavements which satisfy both roughness and skid criteria should be ranked to establish a priority

list of pavement sections for future rehabilitation. Since these pavements also can exhibit some distress, it is also worthwhile to conduct distress surveys on them. This will provide an additional criterion for their ranking.

Do you agree with this idea?

2. Pavement distress inspection crews will rate the sections for different defects, on different scales. These ratings are totaled and the total is subtracted from the maximum rating of 100 ; the result is the pavement condition rating (PCR). Thus, a PCR for any pavement can be any value between 0 and 100, with 100 being that for a "defectless" pavement.

If we were to categorize pavements into two classes: those with acceptable distress and others with unacceptable distress, an acceptable PCR criterion must be defined. In your opinion what such acceptable PCR is appropriate ; please indicate this value for the pavement types and classification of road on the following table.

Acceptable PCR

type	Primary road	Secondary road
flexible		
rigid		

3. In distress survey procedures, the extent of certain types of defects are determined by the percentage of defective area in a 200 foot section containing the defect. Alligator cracks, block cracking, shoving, and patches are such defects for flexible pavements while D-cracking, patching, and pavement break-up correspond to rigid pavements. Since the area determination is not precise, a "range of variation" is introduced in the rating. For example, when a crew rates alligator cracking its support may spread over a range between 3.5 and 6.5 (scale for rating 0.0 to 10.0) due to the uncertainty in the area determination, although it may assign a value of 5.0 because a single value response is required. Thus, the range of variation is ± 1.5 .

Do you agree with this idea?

If so, according to your judgment, what such ranges would you assign for the following defect types?

Note : The worse the defect is, the larger the rating number.

	Type	Scale	Range of variation (±)
	alligator cracks	0-10	
Flexible	block cracking	0-10	
	shoving	0-10	
	patching	0-10	
	D-cracking	0-10	
Rigid	patching	0-10	
	slab break-up	0-10	
	pumping	0-10	
	faulting	0-10	

4. According to the rating instructions, most defects are to be rated in proportion to their severity. All forms of cracking, patching in all types of pavements and pavement slab break-up in rigid pavements fall into this category. Although in the case of cracks, the severity is determined by the crack width, assignment of a "higher" rating for "severe" conditions is suggested.

As an example, assume that crew members rate a section as 3.0 for transverse cracking considering the extent only. Then, once they observe that the cracking is severe (width being greater than 1/4") they are compelled to go for a higher rating. They might consider a range between 2.5 and 5.5 before deciding

on 4.0, to which they give the highest support. In this case the above mentioned interval is defined by ± 1.5 .

Do you agree with this idea?

If so, in your opinion, what such intervals should be attached for the following defects?

	Type	Scale	Interval ($\pm x$)
Flexible	transverse cracks	1-10	
	longitudinal cracks	1-10	
	patching	1-10	
Rigid	pavement break-up	1-10	
	patching	1-10	
	transverse cracks	1-10	
	longitudinal cracks	1-10	
	D-cracking	1-10	

Results obtained from questionnaire No.5

Note: Answers were provided by 19 experts. Each column in the following refers to the answer of an expert.

Table A26. Acceptable PCR.

Question 2.

PRIMARY ROAD

<u>Type of</u> <u>pavement</u>	<u>PCR</u>																		<u>Mn.</u>	<u>S.D.</u>	
Flexible	70	50	65	--	60	50	50	45	35	70	75	70	75	50	50	85	40	90	--	61	16
Rigid	70	50	65	--	60	50	50	40	35	75	80	75	75	60	50	80	40	90	--	62	16

SECONDARY ROAD

<u>Type of</u> <u>pavement</u>	<u>PCR</u>																		<u>Mn.</u>	<u>S.D.</u>	
Flexible	50	40	50	—	50	40	50	50	35	65	65	50	60	50	40	80	30	85	—	52	15
Rigid	50	40	50	—	50	40	50	50	35	70	70	55	60	50	40	75	30	85	—	53	15

(--) indicates that no answer was provided.

The following table summarizes responses to questions 3 and 4.

Questionnaire No. 6 (1)

This is the sixth in a series of questionnaires being forwarded to highway engineers to obtain their expertise on a number of subjective areas in pavement management. Our previous questionnaires addressed areas such as: Pavement serviceability rating; acceptable serviceability; variability associated with Roadmeter; Skid-tester and Dynaflect; and Pavement Condition Ratings.

At present, in the state of Indiana the following performance data are collected at the highway network level. At first, all the pavements are scanned with the Roadmeter. Skid tests are conducted to locate safety hazards. Distress measurements, together with roughness and skid resistance values, are used in making decisions concerning priorities for maintenance or rehabilitation. Deflection measurements are used only as a design tool with distress survey results to determine the thickness of resurfacing, etc.

In Indiana, pavements are identified in three primary categories. The first category has those pavements which present traffic hazards due to inadequate skid resistance, while pavements with unacceptable roughness constitutes the second category. The third and the final category contains the ones with acceptable skid-resistance and roughness.

Immediate attention is given to the first category whereas pavements in the second category are prepared for rehabilitation

during the current year considering a fixed budget. Pavement sections that belong to the third category are prioritized for future rehabilitation, using remaining service life. In Indiana current priority lists are prepared using applicable performance parameters (roughness, skid-resistance and distress data) and traffic data. Since the basis for prioritization for category 3 is different, it will not be discussed further here.

It is understood that decisions regarding relative priority levels are subjective and complex if all the relevant parameters are considered. In order to avoid this, highway experts can be asked to respond to less complicated questions. Then these responses can be methodically combined using new Fuzzy-sets based decision techniques in arriving at the rank for each pavement section. Thus, in this questionnaire we seek subjective responses from you for questions regarding priority levels (maintenance criterion) for the first category of pavements(i.e. acceptable roughness, unacceptable skid resistance)

(1) We know that friction, distress and traffic volume play a major role in determining maintenance priorities for this first category of pavements. In other words prioritization of this first category of pavements can be done using only values of friction, PCR and ADT. In your opinion are these two types of data adequate for this purpose?

If the answer is 'No', please indicate what additional type of data you believe is required.

(2) If we assume that priorities can be numerically represented by values on a scale of 1 - 10 then each combination of <Friction No. , PCR, Avg. Daily Traffic> will determine a value on that scale. This value results from subjective judgment of highway maintenance decision makers.

For example if we assign a range of values of 9.1 - 9.5 as the priority for the combination <FN = 20, PCR = 60 ADT = 8000>, then the priority range for the case of <FN = 30, PCR= 80 ADT = 6000> could be about 8.0 - 8.5; The larger value indicates a higher priority for maintenance.

On the next page, a few such combinations of attribute values are provided. In the appropriate places please indicate priority value ranges (in a scale of 1 - 10) which you think will best describe the maintenance urgency of a pavement that has such attribute values.

(FN , PCR , ADT)	Priority value range
-----	-----
(45 , 70 , 1400)	-----
(35 , 50 , 2000)	-----
(25 , 30 , 2400)	-----
(44 , 73 , 2800)	-----
(40 , 53 , 3200)	-----
(34 , 33 , 3600)	-----
(26 , 13 , 4000)	-----
(43 , 76 , 4400)	-----
(39 , 56 , 4800)	-----
(33 , 36 , 5200)	-----
(27 , 16 , 5800)	-----
(41 , 65 , 6400)	-----
(37 , 40 , 7600)	-----
(29 , 20 , 8800)	-----

The following part of this questionnaire is very similar to the previous part except that it has different primary categories for the pavement sections.

In many states four kinds of performance data are collected at the highway network level. At first, all the pavements are scanned with the Roadmeter. Then skid tests are conducted for pavements with acceptable roughness, while Dynaflect and distress surveys are carried out on the others. Using these measurements, decisions must be made concerning priorities for maintenance or rehabilitation. (Ref. Gunaratne M. et al. "The use of fuzzy sets mathematics in pavement evaluation and management." Purdue University 1984.)

Three primary categories of pavements are identified. The first category has those pavements which present traffic hazards due to inadequate skid resistance, while pavements with unacceptable roughness constitutes the second category. The third and the final category contains the ones with acceptable skid-resistance and roughness.

Taking into account the experience of many states, the following attributes are suggested for setting up priorities for pavements in the first and second category. The results of condition surveys i.e. PCR are of prime importance in creating priorities for the worst performing sections (second category), since a distress survey considers the factors that are relevant to their rehabilitation. On the other hand, for pavement sections in

the first category, skid resistance appears to be an obvious attribute for creating priorities. In addition, traffic data, represented by ADT, should play a significant role for both categories. It should be noted that PSI is involved in the scheme only as a means for determining to which category the section belongs.

Immediate attention is given to the first category whereas pavements in the second category are prepared for maintenance during the current year considering a fixed budget. Pavement sections that belong to the third category are prioritized for future rehabilitation, using remaining service life. As it is practiced in most states (including Indiana to a certain extent), current priority lists (for categories 1 and 2) are prepared using applicable performance parameters (roughness, structural adequacy, skid-resistance and distress data) and traffic data. Since the basis for prioritization for category 3 is different, it will not be discussed further here.

It is understood that decisions regarding relative priority levels are subjective and complex if all the relevant parameters are considered. In order to avoid this, highway experts can be asked to respond to less complicated questions. Then these responses can be methodically combined using new Fuzzy-sets based decision techniques in arriving at the rank for each pavement section. Thus, in this questionnaire we seek subjective responses from you for questions regarding priority levels for the first category (i.e. acceptable roughness, unacceptable skid

resistance)

(1) We know that friction and traffic volume play a major role in determining maintenance priorities for this first category of pavements. In your opinion are these two types of data adequate for this purpose?

If the answer is "No", please indicate what additional type of data you believe is required.

(2) If we assume that priorities can be numerically represented by values on a scale of 1 - 10 then each combination of <Friction No. , Avg. Daily Traffic> will determine a value on that scale. This value results from subjective judgment of highway maintenance decision makers.

For example if we assign a range of values of 9.1 - 9.5 as the priority for the combination <FN = 20, ADT = 8000>, then the priority range for the case of <FN = 30, ADT = 6000> could be about 8.0 - 8.5; The larger value indicates a higher priority for maintenance.

On the next page, few such combinations of attribute values are provided. In the appropriate places please indicate priority value ranges (in a scale of 1 - 10) which you think will best describe the maintenance urgency of a pavement that has such attribute values.

(FN , ADT)	Priority value range
-----	-----
(45 , 1400)	-----
(35 , 2000)	-----
(25 , 2400)	-----
(44 , 2800)	-----
(40 , 3200)	-----
(34 , 3600)	-----
(26 , 4000)	-----
(43 , 4400)	-----
(39 , 4800)	-----
(33 , 5200)	-----
(27 , 5800)	-----
(41 , 6400)	-----
(37 , 7600)	-----
(29 , 8800)	-----

Results obtained from questionnaire No.6 (i)

Table A28. (ADT , FN , PCR).

Note that each row in the following results represents the opinion of an individual expert (utility values and their possible range).
Question No.2 of the first part.

(1400,45,70) (2000,35,50) (2400,25,30) (2800,44,73) (3200,40,53)

7.0,0.4	8.0,0.4	9.4,0.4	7.1,0.4	7.5,0.4
2.0,0.5	5.0,5.5	7.0,0.5	2.0,0.5	5.0,0.5
2.0,0.9	5.0,0.9	8.0,0.9	2.0,0.9	5.0,0.9
7.0,0.5	8.0,0.5	10.0,0.	7.5,0.5	8.0,0.5
0.0,1.0	0.5,1.0	8.0,1.0	0.5,0.5	0.5,1.0
--	--	--	--	--
7.0,0.5	8.0,0.5	9.0,0.5	7.0,0.5	8.5,0.5
3.0,0.5	7.5,0.5	9.2,0.5	4.0,0.5	5.0,0.5
8.5,0.4	8.9,0.4	9.3,0.4	8.4,0.4	8.8,0.4
1.0,0.1	4.0,0.5	6.8,0.5	1.9,0.5	3.4,0.5
1.0,0.5	6.0,0.5	7.0,0.5	2.0,0.5	6.2,0.5
3.0,0.5	4.0,0.5	5.5,0.5	3.5,0.4	5.0,0.5
8.1,0.2	9.2,0.3	9.4,0.3	8.1,0.3	9.1,0.3
2.0,2.0	4.0,2.0	6.0,2.0	2.0,2.0	4.0,2.0
3.5,0.5	5.0,0.5	6.0,6.5	4.0,0.5	5.0,0.5
1.0,1.0	6.0,1.0	7.0,1.0	2.0,1.0	6.5,1.0
3.0,0.5	5.0,0.5	7.5,0.5	5.0,0.5	5.0,0.5
2.0,2.0	4.0,2.0	8.0,2.0	4.0,2.0	6.0,2.0
2.0,1.0	5.0,1.0	7.5,0.5	2.0,1.0	6.5,0.5

(3600,34,33) (4000,26,13) (4400,43,76) (4800,39,56) (5200,33,36)

8.2,0.4	9.5,0.4	7.2,0.4	7.6,0.4	9.2,0.4
6.5,0.5	9.5,0.5	2.0,0.5	5.5,0.5	6.0,0.5
6.0,0.9	8.0,0.9	3.0,0.9	6.0,0.9	7.0,0.9
8.5,0.5	10.0,0.	7.5,0.5	8.0,0.5	9.0,0.5
8.0,1.0	9.5,0.5	2.5,1.5	3.0,1.0	9.0,1.0
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9.0,0.5	9.5,0.5	7.0,0.5	8.0,0.5	9.0,0.5
8.9,0.5	9.5,0.5	6.0,0.5	8.0,0.5	9.0,0.5
9.2,0.4	9.6,0.4	8.3,0.4	8.7,0.4	9.1,0.4
5.2,0.5	7.7,0.5	2.1,0.5	3.9,0.5	6.1,0.5
8.0,0.5	9.0,0.5	1.3,0.5	7.5,0.5	8.3,0.5
6.5,0.5	8.0,0.5	4.5,0.5	6.0,0.5	7.5,0.5
9.4,0.3	9.7,0.2	8.2,0.4	9.2,0.2	9.4,0.3
5.0,2.0	6.0,2.0	2.0,2.0	4.0,2.0	2.0,4.0
6.0,0.5	7.0,0.5	4.5,0.5	5.5,0.5	6.5,0.5
8.5,1.0	9.0,1.0	2.0,1.0	6.5,7.5	8.5,1.0
7.5,0.5	8.0,0.5	5.0,0.5	7.0,0.5	8.0,0.5
8.0,2.0	8.0,2.0	4.0,2.0	6.0,2.0	8.0,2.0
7.5,0.5	9.0,0.5	5.0,1.0	7.0,0.5	8.0,0.5

Table A28. (Continued).

(5800,27,16) (6400,41,65) (7600,37,40) (8800,29,20) (1000,80,90)

9.5,0.4	7.3,0.4	8.6,0.4	9.6,0.4	4.0,0.4
9.5,0.5	4.0,0.5	5.0,0.5	9.0,0.5	1.0,0.5
9.0,0.9	5.0,0.9	7.0,0.9	9.0,0.9	1.0,0.9
10.,0.0	7.5,0.5	9.0,0.5	10.0,0.	4.0,0.5
9.5,0.5	7.5,1.0	8.0,1.0	9.5,0.5	0.0,1.0
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9.5,0.5	7.0,0.5	9.0,0.5	9.5,0.5	3.0,0.5
9.5,0.5	6.5,0.5	8.5,0.5	9.3,0.5	1.0,0.5
9.5,0.4	8.6,0.4	9.0,0.4	9.4,0.4	4.0,0.4
8.0,0.5	3.5,0.5	6.0,0.5	9.5,0.5	0.5,0.1
9.3,0.5	7.0,0.5	9.3,0.5	9.5,0.5	0.5,0.5
9.0,0.5	7.0,0.5	8.5,0.5	9.5,0.5	1.0,0.5
9.7,0.2	8.7,0.3	9.5,0.2	9.8,0.2	3.0,0.2
6.0,2.0	2.0,4.0	4.0,2.0	6.0,2.0	1.0,2.0
7.5,0.5	5.5,0.5	7.0,0.5	8.5,0.5	1.0,0.5
9.0,1.0	7.0,1.0	8.0,1.0	10.0,0.	0.5,1.0
9.1,0.4	6.0,0.5	7.0,0.5	9.1,0.4	1.0,0.5
8.0,2.0	6.0,2.0	8.0,2.0	8.0,2.0	1.0,2.0
9.0,0.5	7.0,0.5	8.0,1.0	9.0,0.5	1.0,1.0

(10200,11,9)

9.8,0.2
 9.5,0.5
 9.5,0.5
 10.0,0.0
 9.8,0.2

 9.8,0.2
 9.6,0.4
 9.8,0.2
 9.9,0.1
 9.9,0.1
 9.9,0.1
 10.0,0.0
 9.0,1.0
 9.3,0.7
 10.0,1.0
 9.8,0.2
 9.2,0.8
 9.7,0.3

Table A29. (FN , ADT).

Question No.2 of the second part.

<u>(45,1400)</u>	<u>(35,2000)</u>	<u>(25,2400)</u>	<u>(44,2800)</u>	<u>(40,3200)</u>	<u>(34,3600)</u>
7.0,0.4	8.5,0.4	9.2,0.4	7.2,0.4	7.3,0.4	8.0,0.4
3.0,0.5	4.0,0.5	7.0,0.5	3.0,0.5	3.5,0.5	5.0,0.5
3.0,0.9	6.0,0.9	8.0,0.9	4.0,0.9	5.0,0.9	7.0,0.9
5.0,0.5	6.0,0.5	10.0,0.	5.0,0.5	6.0,0.5	8.0,0.5
0.0,0.0	2.0,1.0	8.0,0.5	0.5,0.5	1.0,0.5	7.5,1.0
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5.0,0.5	8.0,0.5	9.5,0.5	4.5,0.5	5.0,0.5	8.0,0.5
3.0,0.5	7.5,0.5	9.3,0.5	5.5,0.5	6.0,0.5	8.0,0.5
0.0,0.4	0.9,0.4	9.0,0.4	0.1,0.4	6.0,0.4	1.1,0.3
0.0,0.5	3.2,0.5	6.1,0.5	1.0,1.5	1.7,0.5	4.1,0.5
1.0,0.5	3.0,0.5	6.5,0.5	1.5,0.5	3.0,0.5	4.5,0.5
3.0,0.5	4.0,0.5	7.0,0.5	3.5,0.5	4.5,0.5	5.5,0.5
7.0,0.2	8.2,0.4	9.4,0.4	7.3,0.2	7.8,0.5	8.4,0.5
2.0,2.0	4.0,2.0	4.0,2.0	2.0,2.0	2.0,2.0	4.0,2.0
3.5,0.5	4.5,0.5	5.0,0.5	4.5,0.5	5.0,0.5	5.5,0.5
2.0,1.0	4.0,1.0	6.0,1.0	4.0,1.0	5.5,1.0	6.0,1.0
1.0,0.5	7.0,0.5	8.5,0.5	3.0,0.5	6.0,0.5	7.5,0.5
6.0,2.0	8.0,2.0	8.0,2.0	6.0,2.0	6.0,2.0	8.0,2.0
3.0,1.0	4.0,1.0	6.0,1.0	5.0,1.0	5.0,1.0	6.0,1.0
<u>(26,4000)</u>	<u>(43,4400)</u>	<u>(39,4800)</u>	<u>(33,5200)</u>	<u>(27,5800)</u>	<u>(41,6400)</u>
9.3,0.4	7.3,0.4	7.2,0.4	8.2,0.4	9.4,0.4	7.4,0.4
7.0,0.5	3.0,0.5	4.0,0.5	6.0,0.5	8.0,0.5	3.5,0.5
9.0,0.9	5.0,0.9	6.0,0.9	8.0,0.9	9.0,0.9	6.0,0.9
10.0,0.	7.0,0.5	7.0,0.5	9.0,0.5	10.0,0.	8.5,0.5
8.5,1.0	2.5,1.0	7.5,8.5	8.5,9.5	9.0,1.0	4.5,1.0
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9.0,0.5	4.5,0.5	5.0,0.5	8.0,0.5	9.0,0.5	5.0,0.5
9.4,0.5	6.5,0.5	7.3,0.4	9.0,0.2	9.5,0.5	7.4,0.4
8.9,0.4	0.2,0.4	0.5,0.4	1.4,0.4	8.8,0.4	0.3,0.4
6.4,0.5	1.8,0.5	3.1,0.5	5.5,0.5	7.4,0.5	3.4,0.5
8.0,0.5	2.0,0.5	4.0,0.5	5.5,0.5	8.5,0.5	2.5,0.5
7.5,0.5	5.0,0.5	6.0,0.5	8.0,0.5	9.0,0.5	6.5,0.5
9.4,0.4	7.6,0.4	8.0,0.5	8.6,0.4	9.1,0.4	7.9,0.5
7.0,2.0	6.0,2.0	6.0,2.0	6.0,2.0	7.0,2.0	6.0,2.0
6.0,0.5	5.5,0.5	5.5,0.5	6.0,0.5	7.0,0.5	6.5,0.5
8.0,1.0	6.0,1.0	6.0,1.0	7.5,1.0	8.0,1.0	7.0,1.0
8.5,0.5	5.0,0.5	6.5,0.5	7.5,0.5	8.5,0.5	6.0,0.5
8.0,2.0	6.0,2.0	8.0,2.0	8.0,2.0	8.0,2.0	6.0,2.0
8.0,1.0	6.0,1.0	7.0,1.0	8.0,1.0	9.0,1.0	8.0,1.0

Table A29. (Continued)

(37,7600) (29,8800)

8.4,0.4	9.5,0.4
3.0,0.5	8.0,0.5
8.0,0.9	9.0,0.9
8.5,0.5	10.0,0.
9.0,0.5	9.5,0.5
--	--
6.0,0.5	8.5,0.5
8.5,0.5	9.6,0.4
0.7,0.2	8.3,0.4
5.7,0.5	9.5,0.5
5.0,0.5	9.0,0.5
8.5,0.5	9.5,0.5
8.2,0.4	9.0,0.4
8.0,2.0	8.0,2.0
7.0,0.5	8.0,0.5
8.0,1.0	9.0,1.0
7.5,0.5	8.5,0.5
6.0,2.0	8.0,2.0
9.0,1.0	9.0,1.0

Questionnaire No. 6 (ii)

This is the second part of sixth in a series of questionnaires being forwarded to highway engineers to obtain their expertise on a number of subjective areas in pavement management. Our previous questionnaires addressed areas such as: Pavement serviceability rating; acceptable serviceability variability associated with Roadmeter, Skid-tester and Dynaflect; and Pavement Condition Ratings.

At present, in the state of Indiana the following performance data are collected at the highway network level. At first, all the pavements are scanned with the Roadmeter. Skid tests are conducted to locate safety hazards. Distress measurements, together with roughness and skid resistance values, are used in making decisions concerning priorities for maintenance or rehabilitation. Deflection measurements are used only as a design tool with distress survey results to determine the thickness of resurfacing, etc.

In Indiana, pavements are identified in three primary categories. The first category has those pavements which present traffic hazards due to inadequate skid resistance, while pavements with unacceptable roughness constitutes the second category. The third and the final category contains the ones with acceptable skid-resistance and roughness.

Immediate attention is given to the first category whereas pavements in the second category are prepared for rehabilitation

during the current year considering a fixed budget. Pavement sections that belong to the third category are prioritized for future rehabilitation, using remaining service life. In Indiana current priority lists are prepared using applicable performance parameters (roughness, skid-resistance and distress data) and traffic data. Since the basis for prioritization for category 3 is different, it will not be further discussed here.

It is understood that decisions regarding relative priority levels are subjective and complex if all the relevant parameters are considered. In order to avoid this, highway experts can be asked to respond to less complicated questions. Then these responses can be methodically combined using new fuzzy-sets based decision techniques in arriving at a rank for each pavement section. Thus, in this questionnaire we seek subjective responses from you for simple questions regarding priority levels (rehabilitation criterion) for the second category of pavements (i.e. unacceptable roughness)

(1) Once pavements have been categorized according to their PSI (roughness) we propose that the pavement sections in this second category (with unacceptable PSI) be prioritized using the results of distress, roughness and traffic surveys. In other words, prioritization of this second category of pavements can be done using only values of PCR, PSI, and ADT.

Do you agree with this idea?

If your answer is "yes" please proceed to question No. 2.

If your answer is "no", what other parameters are necessary in your opinion for the prioritization of the second category of pavements?

(2) If we assume that priorities can be numerically represented by values on the scale of 1 - 10, each combination of <PSI, PCR, ADT> will determine a value on that scale. This value results from subjective judgment of highway maintenance decision makers.

For example, if we assign a range of values of 9.0 - 9.5 for the combination <PSI = 1.5, PCR = 15.0 and ADT = 8000>, then a possible priority value range for the combination <PSI = 2.0, PCR = 25.0 and ADT = 6000> could be 7.5 - 8.0. The larger value indicates a higher priority for maintenance.

On the next page, we provide a few such combinations of attribute values. In the appropriate places please indicate a priority value range (in a scale of 1 - 10) which you think will best describe the rehabilitation urgency of a pavement that has such attribute values.

(PSI , PCR , ADT)

Priority value range

(2.6 , 70 , 1400)

(2.1 , 50 , 2000)

(1.7 , 30 , 2400)

(2.9 , 73 , 2800)

(2.4 , 53 , 3200)

(1.9 , 33 , 3600)

(1.4 , 13 , 4000)

(2.7 , 76 , 4400)

(2.2 , 56 , 4800)

(1.6 , 36 , 5200)

(1.1 , 16 , 5800)

(2.6 , 65 , 6400)

(2.0 , 40 , 7600)

(1.2 , 20 , 8800)

The following part of this questionnaire is very similar to the previous part except that it has different primary categories for the pavement sections.

In many states four kinds of performance data are collected at the highway network level. At first, all the pavements are scanned with the Roadmeter. Then skid tests are conducted for pavements with acceptable roughness, while Dynaflect and distress surveys are carried out on the others. Using these measurements, decisions must be made concerning priorities for maintenance or rehabilitation. (Ref. Gunaratne M. et al. 'The use of Fuzzy sets mathematics in pavement evaluation and management. Purdue University 1984)

Three primary categories of pavements are identified. The first category has those pavements which present traffic hazards due to inadequate skid resistance, while pavements with unacceptable roughness constitutes the second category. The third and the final category contains the ones with acceptable skid-resistance and roughness.

Taking into account the experience of many states, the following attributes are suggested for setting up priorities for pavements in the first and second category. The results of condition surveys i.e. PCR are of prime importance in creating priorities for the worst performing sections (second category), since a distress survey considers the factors that are relevant to their rehabilitation. On the other hand, for pavement sections in

the first category, skid resistance appears to be an obvious attribute for creating priorities. In addition, traffic data, represented by ADT, should play a significant role for both categories. It should be noted that PSI is involved in the scheme only as a means for determining to which category the section belongs.

Immediate attention is given to the first category whereas pavements in the second category are prepared for maintenance during the current year considering a fixed budget. Pavement sections that belong to the third category are prioritized for future rehabilitation, using remaining service life. As it is practiced in most states (including Indiana to a certain extent), current priority lists (for categories 1 and 2) are prepared using applicable performance parameters (roughness, structural adequacy, skid-resistance and distress data) and traffic data. Since the basis for prioritization for category 3 is different, it will not be discussed further here.

It is understood that decisions regarding relative priority levels are subjective and complex if all the relevant parameters are considered. In order to avoid this, highway experts can be asked to respond to less complicated questions. Then these responses can be methodically combined using new fuzzy-sets based decision techniques in arriving at a rank for each pavement section. Thus, in this questionnaire we seek subjective responses from you for simple questions regarding priority levels for the second category (i.e. unacceptable roughness)

(1) Once pavements have been categorized according to their PSI (roughness) we propose that the pavement sections in this second category (with unacceptable PSI) be prioritized using the results of distress, Dynaflect and traffic surveys. In other words, prioritization of this second category of pavements can be done using only values of PCR, deflections, and ADT.

Do you agree with this idea?

If your answer is `yes` please proceed to question No. 2.

If your answer is `no`, what other parameters are necessary in your opinion for the prioritization of the second category of pavements?

(2) If we assume that priorities can be numerically represented by values on the scale of 1 - 10, each combination of <deflection, PCR, ADT> will determine a value on that scale. This value results from subjective judgment of highway maintenance decision makers.

For example, if we assign a range of values of 9.0 - 9.5 for the combination <def. = 1.1 mils, PCR = 15 and ADT = 8000>, then a possible priority value range for the combination <def. = 0.9 mils, PCR = 25.0 and ADT = 6000> could be 7.5 - 8.0. The larger value indicates a higher priority for maintenance.

On the following page, we provide a few such combinations of attribute values. In the appropriate places please indicate a priority value range (in a scale of 1 - 10) which you think will

best describe the maintenance urgency of a pavement that has such attribute values.

(def. , PCR , ADT)

Priority value range

(1.5 , 70 , 1400)

(2.0 , 50 , 2000)

(2.5 , 30 , 2400)

(1.1 , 73 , 2800)

(1.6 , 53 , 3200)

(2.1 , 33 , 3600)

(2.6 , 13 , 4000)

(1.2 , 76 , 4400)

(1.7 , 56 , 4800)

(2.2 , 36 , 5200)

(2.7 , 16 , 5800)

(1.3 , 65 , 6400)

(1.8 , 40 , 7600)

(2.3 , 20 , 8800)

Results obtained from questionnaire No.6 (11).

Table A30. (ADT , PSI , PCR).

Note that each row in the following results represents the opinion of an individual expert (utility values and their possible range). Question No.2 of the first part.

(1400,2.6,70) (2000,2.1,50) (2400,1.7,30) (2800,2.9,73) (3200,2.4,53)

7.2,0.4	7.8,0.4	9.2,0.4	7.1,0.4	8.0,0.4
2.0,0.5	4.0,0.5	8.0,0.5	2.5,0.5	4.0,0.5
2.0,0.9	5.0,0.9	7.0,0.9	3.0,0.9	6.0,0.9
8.0,0.5	9.0,0.5	9.0,0.5	8.0,0.5	9.0,0.5
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3.5,0.5	5.0,0.5	6.0,0.5	2.5,0.5	4.0,0.5
5.0,0.5	8.0,0.5	9.0,0.5	6.0,0.5	7.5,0.5
4.6,0.4	7.3,0.5	8.5,0.5	5.0,0.4	7.0,0.5
8.3,0.4	8.9,0.4	9.2,0.4	8.2,0.4	8.8,0.4
1.3,0.5	3.6,0.4	5.5,0.5	1.0,0.5	3.3,0.5
2.0,0.5	4.0,0.5	6.0,0.5	2.0,0.5	4.0,0.5
3.5,0.5	4.5,0.5	7.0,0.5	3.0,0.5	5.0,0.5
7.8,0.4	9.0,0.4	9.6,0.3	7.7,0.3	9.0,0.5
7.0,2.0	4.0,2.0	2.0,2.0	8.0,2.0	4.0,2.0
3.5,0.5	4.5,0.5	5.5,0.5	3.5,0.5	4.5,0.5
2.0,1.0	4.5,1.0	7.0,1.0	2.5,1.0	5.0,1.0
4.0,0.5	6.0,0.5	7.0,0.5	3.5,0.5	6.0,0.5
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6.0,1.0	7.0,1.0	8.0,1.0	5.0,1.0	7.0,1.0

(3600,1.9,33) (4000,1.4,13) (4400,2.7,76) (4800,2.2,56) (5200,1.6,36)

9.1,0.4	9.2,0.4	7.4,0.4	7.2,0.4	9.2,0.4
8.0,0.5	9.5,0.5	2.0,0.5	4.0,0.5	6.0,0.5
8.0,0.9	8.0,0.9	4.0,0.9	6.0,0.9	8.0,0.9
9.0,0.5	9.5,0.5	8.0,0.5	9.0,0.5	9.5,0.5
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6.5,0.5	7.0,0.5	3.0,0.5	5.5,0.5	7.5,0.5
8.5,0.5	9.5,0.5	6.0,0.5	7.5,0.5	9.0,0.5
8.0,0.5	9.5,0.5	5.5,0.4	7.2,0.5	8.7,0.5
9.1,0.4	9.5,0.4	8.1,0.4	8.9,0.4	9.1,0.4
5.6,0.5	7.7,0.5	2.9,0.5	4.5,0.5	6.8,0.5
6.0,0.5	7.5,0.5	2.0,0.5	5.0,0.5	7.5,0.5
7.5,0.5	8.5,0.5	4.0,0.5	6.0,0.5	6.5,0.5
9.4,0.4	9.7,0.2	8.0,0.4	9.0,0.5	9.6,0.3
2.0,2.0	3.0,2.0	7.0,2.0	4.0,2.0	1.0,2.0
5.5,0.5	7.0,0.5	4.0,0.5	5.0,0.5	6.5,0.5
7.5,1.0	9.0,1.0	3.0,1.0	5.0,1.0	8.0,1.0
7.5,0.5	9.0,0.5	3.5,0.5	7.0,0.5	8.0,0.5
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8.0,1.0	9.0,1.0	5.0,1.0	7.0,1.0	8.0,1.0

Table A30. (Continued)

(5800,1.1,16) (6400,2.6,65) (7600,2.0,40) (8800,1.2,20) (1000,3.2,90)

9.5,0.4	7.5,0.4	8.1,0.4	9.4,0.4	5.0,0.4
9.5,0.5	2.5,0.5	6.0,0.5	9.5,0.5	1.0,0.5
9.0,0.9	5.0,0.9	8.0,0.9	9.0,0.9	1.0,0.9
9.5,0.5	8.5,0.5	9.0,0.5	9.5,0.5	5.0,0.5
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8.5,0.5	4.5,0.5	8.0,0.5	9.0,0.5	2.0,0.5
9.5,0.5	7.0,0.5	8.5,0.5	9.5,0.5	3.0,0.5
9.5,0.5	6.0,0.5	7.7,0.5	9.0,0.5	2.0,0.4
9.5,0.4	8.5,0.4	9.0,0.4	9.4,0.4	3.0,0.4
9.0,0.5	4.4,0.5	5.8,0.5	9.5,0.5	0.5,0.5
8.5,0.5	4.0,0.5	6.5,0.5	9.0,0.5	1.0,0.5
9.0,0.5	5.5,0.5	8.0,0.5	9.5,0.5	2.0,0.5
9.7,0.2	8.2,0.4	9.4,0.4	9.7,0.3	3.0,0.4
1.0,2.0	4.0,2.0	4.0,2.0	3.0,2.0	4.0,2.0
7.5,0.5	5.0,0.5	5.5,0.5	8.5,0.5	1.0,0.5
9.0,1.0	5.5,1.0	8.5,1.0	9.0,1.0	1.0,1.0
9.5,0.5	6.0,0.5	7.5,0.5	9.0,0.5	2.0,0.5
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9.0,1.0	6.0,1.0	8.0,1.0	9.0,1.0	4.0,1.0

(10200,0.9,9)

9.8,0.2
 9.7,0.3
 9.5,0.5
 9.7,0.3

 9.3,0.7
 9.7,0.3
 9.5,0.5
 9.8,0.2
 9.8,0.2
 9.5,0.5
 9.9,0.1
 9.9,0.1
 8.0,2.0
 9.3,0.7
 9.5,0.5
 9.8,0.2

 9.8,0.2

Table A31. (Def., PCR , ADT).

Question No.2 of the second part.

(1.5,70,1400) (2.0,50,2000) (2.5,30,2400) (1.1,73,2800) (1.6,53,3200)

7.2,0.4	8.8,0.4	9.1,0.4	7.2,0.4	7.4,0.4
3.0,0.5	4.5,0.5	5.5,0.5	3.0,0.5	4.0,0.5
3.0,0.9	4.0,0.9	4.0,0.9	4.0,0.9	6.0,0.9
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2.5,0.5	4.5,0.5	7.0,0.5	3.0,0.5	3.5,0.5
7.0,0.5	8.5,0.5	9.0,0.5	8.0,0.5	7.5,0.5
4.0,0.5	8.5,0.5	9.0,0.5	5.0,0.5	7.8,0.5
8.8,0.4	9.2,0.4	9.5,0.4	8.7,0.4	9.0,0.4
1.7,0.5	4.4,0.5	7.0,0.5	1.0,0.5	3.6,0.5
3.0,0.5	4.0,0.5	5.0,0.5	3.0,0.5	4.0,0.5
3.5,0.5	5.0,0.5	7.0,0.5	3.0,0.5	4.5,0.5
7.6,0.6	9.0,0.5	9.3,0.4	7.0,0.5	8.8,0.5
7.0,2.0	6.0,2.0	4.0,2.0	7.0,2.0	3.0,2.0
4.0,0.5	4.5,0.5	5.0,0.5	4.5,0.5	5.0,0.5
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7.0,0.5	8.0,0.5	8.5,0.5	6.5,0.5	7.5,0.5
2.0,2.0	4.0,2.0	6.0,2.0	2.0,2.0	4.0,2.0
1.0,1.0	3.0,1.0	5.0,1.0	2.0,1.0	4.0,1.0

(2.1,33,3600) (2.6,13,4000) (1.2,76,4400) (1.7,56,4800) (2.2,36,5200)

8.9,0.4	9.5,0.4	7.1,0.4	7.6,0.4	9.0,0.4
5.5,0.5	9.0,0.5	3.0,0.5	4.5,0.5	5.5,0.5
6.0,0.9	6.0,0.9	5.0,0.9	7.0,0.9	8.0,0.9
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6.5,0.5	8.5,0.5	4.0,0.5	5.0,0.5	7.5,0.5
8.5,0.5	9.5,0.5	8.0,0.5	7.5,0.5	8.8,0.2
8.7,0.5	9.5,0.5	6.0,0.5	8.0,0.5	8.7,0.5
9.4,0.4	9.6,0.4	8.7,0.4	9.0,0.4	9.4,0.4
6.3,0.5	9.0,0.5	1.9,0.5	4.6,0.5	7.2,0.5
5.0,0.5	7.0,0.5	3.0,0.5	5.0,0.5	7.0,0.5
6.5,0.5	8.5,0.5	4.0,0.5	6.0,0.5	8.0,0.5
9.1,0.4	9.4,0.4	7.4,0.4	8.9,0.5	9.3,0.4
3.0,2.0	3.0,2.0	7.0,2.0	4.0,2.0	4.0,2.0
5.5,0.5	6.0,0.5	5.0,0.5	5.5,0.5	6.0,0.5
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8.5,0.5	9.5,0.5	7.0,0.5	8.0,0.5	9.0,0.5
8.0,2.0	8.0,2.0	2.0,2.0	4.0,2.0	8.0,2.0
5.0,1.0	8.0,1.0	2.0,1.0	4.0,1.0	7.0,1.0

Table A31. (Continued)

(2.7,16,5800) (1.3,65,6400) (1.8,40,7600) (2.3,20,8800)

9.6,0.4	7.4,0.2	8.8,0.4	9.3,0.4
9.0,0.5	4.0,0.5	5.0,0.5	8.5,0.5
9.0,0.9	7.0,0.9	8.0,0.9	9.0,0.9
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9.0,0.5	5.5,0.5	6.0,0.5	8.0,0.5
9.5,0.5	8.0,0.5	7.5,0.5	9.0,0.5
9.5,0.5	7.0,0.5	8.5,0.5	9.2,0.5
9.6,0.4	8.9,0.4	9.2,0.4	9.6,0.4
9.9,0.5	3.7,0.5	7.0,0.5	10.0,0.
8.5,0.5	6.0,0.5	8.0,0.5	9.5,0.5
9.5,0.5	5.5,0.5	7.5,0.5	9.0,0.5
9.5,0.4	7.8,0.5	9.2,0.5	9.4,0.4
4.0,2.0	8.0,2.0	7.0,2.0	4.0,2.0
6.5,0.5	6.0,0.5	7.0,0.5	7.5,0.5
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9.5,0.5	7.5,0.5	8.5,0.5	9.5,0.5
8.0,2.0	2.0,2.0	8.0,2.0	8.0,2.0
8.0,1.0	4.0,1.0	7.0,1.0	9.0,1.0

Questionnaire No. 7

This is the seventh in a series of questionnaires sent to highway experts to seek their opinion on certain areas of pavement management that involves human based uncertainty. Four kinds of data are collected to determine performance of highway pavements in Indiana, namely roughness, skid-resistance, distress and deflection data. Decisions concerning priorities for maintenance are made based on these data as well as subjective judgment of highway engineers.

In Indiana, as in many other states, three categories of pavements are identified for maintenance at different stages. The first category has those pavements which present traffic hazards due to inadequate skid resistance, while pavements with unacceptable roughness constitute the second category. All the pavement sections falling under the above categories need immediate attention, The two preceding questionnaires addressed subjectiveness associated with prioritization of these of pavements.

The third and the final category contains pavement sections with acceptable skid-resistance as well as roughness. In this questionnaire we are concerned with the subjectivity involved in the prioritization of these, still serviceable pavements, for future rehabilitation.

(1) The Pavement Management Task Force of the Indiana Department of Highways has proposed collecting condition data on all pavement sections instead of only on unacceptably rough

sections, as one of its short term objectives. This will provide yet another criterion for prioritization of the third category of pavements.

Do you agree with this idea?

(2) Many variables must be considered in ranking pavement sections for future maintenance with the most important ones being remaining PSI and friction lives and ADT for the section. Since ADT is major factor in both types of service lives, once the service lives are used as two pertinent attributes, the inclusion of ADT seems redundant. Therefore, we suggest that prioritization of pavements in Category 3 can be done using only the service lives as attributes.

Do you agree with this idea?

(3) We know that prioritization of highway pavements for future rehabilitation involves multi-attribute decisions, i.e., assigned rankings depend on the remaining PSI life and remaining friction life of the particular pavement. Thus, if we assume that priorities can be represented numerically by the scale 1 - 10, each combination <PSI life, FN life> will determine a value on that scale. With the knowledge of the above two parameters for the section, a decision maker would be able to assign a ranking to the section, using his experience.

As an example, if we assign a priority range of values of 8.0 - 8.5 for the combination

<PSI life = 3.2 yrs, FN life = 2.2 yrs>,
then the combination of

<PSI life = 2.2 yrs, FN life = 3.2 yrs>,
would have to be assigned a lower priority value, say 6.8 - 7.0.
The larger value indicates a higher priority for future maintenance.

In the table below, we provide a few such combinations of attribute values. In the appropriate places, please indicate a priority value range (in a scale of 1 - 10), which you think will best describe the future maintenance urgency of a pavement that has such attribute values.

FN LIFE	PSI LIFE			
	2.0	4.0	6.0	8.0
1.0				
3.0				
5.0				
7.0				

Results obtained from questionnaire No.7.

Table A32. (FN life,PSI life) in years.

Note that each row in the following results represents the opinion of an individual expert (utility values and their possible range). Question 3.

<u>(1.00,2.00)</u>	<u>(1.00,4.00)</u>	<u>(1.00,6.00)</u>	<u>(1.00,8.00)</u>	<u>(3.00,2.00)</u>	<u>(3.00,4.00)</u>
10.0,0.	9.0,0.0	9.0,0.0	8.0,0.0	9.0,0.0	8.0,0.0
9.5,0.0	8.0,0.0	7.0,0.0	6.0,0.0	9.0,0.0	7.0,0.0
9.0,0.9	8.0,0.9	7.0,0.9	6.0,0.9	8.0,0.9	7.0,0.9
9.5,0.5	9.0,0.5	8.5,0.5	8.0,0.5	9.5,0.5	9.0,0.5
9.5,0.5	9.5,0.5	9.0,1.0	9.0,0.5	9.0,1.0	8.5,0.5
9.0,0.5	7.0,0.5	5.0,0.5	3.0,0.5	8.5,0.5	6.5,0.5
10.0,0.	8.0,0.0	7.0,0.0	7.0,0.0	8.0,0.0	7.0,0.0
9.5,0.5	9.0,0.5	8.5,0.5	8.0,0.5	9.0,0.5	7.0,0.5
10.0,0.	9.3,0.0	8.7,0.0	8.0,0.0	--	--
10.0,0.	8.1,0.0	7.7,0.0	7.3,0.0	6.4,0.0	6.0,0.0
9.5,0.5	8.0,0.5	7.0,0.5	5.5,0.5	8.0,0.5	7.0,0.5
9.5,0.5	9.0,0.5	8.5,0.5	8.0,0.5	9.0,0.5	8.5,0.5
9.5,0.3	9.0,0.4	8.8,0.5	8.8,0.5	9.4,0.4	8.9,0.4
9.5,0.0	9.0,0.0	7.0,0.0	5.0,0.0	8.0,0.0	7.0,0.0
9.5,0.5	9.5,0.5	9.0,0.5	9.0,0.5	9.0,0.5	8.0,0.5
8.0,1.0	7.0,1.0	4.0,1.0	3.0,1.0	7.5,1.0	6.0,1.0
9.5,0.5	9.0,0.5	8.5,0.5	8.0,0.5	8.0,0.5	7.0,0.5
8.0,2.0	8.0,2.0	6.0,2.0	6.0,2.0	8.0,2.0	6.0,2.0
9.5,0.5	9.0,0.5	8.7,0.5	8.2,0.5	8.8,0.5	7.6,0.5
<u>(3.00,6.00)</u>	<u>(3.00,8.00)</u>	<u>(5.00,2.00)</u>	<u>(5.00,4.00)</u>	<u>(5.00,6.00)</u>	<u>(5.00,8.00)</u>
6.0,0.0	4.0,0.0	8.0,0.0	7.0,0.0	5.0,0.0	2.0,0.0
6.0,0.0	5.0,0.0	8.0,0.0	6.0,0.0	4.0,0.0	3.0,0.0
6.0,0.9	6.0,0.9	8.0,0.9	6.0,0.9	5.0,0.9	4.0,0.9
8.5,0.5	8.0,0.5	9.0,0.5	8.5,0.5	8.0,0.5	7.5,0.5
8.5,0.5	8.0,1.0	8.0,1.0	8.0,0.5	7.0,1.0	6.5,0.5
4.5,0.5	2.5,0.5	8.0,0.5	6.0,0.5	4.0,0.5	2.0,0.5
5.0,0.0	4.0,0.0	7.0,0.0	5.0,0.0	4.0,0.0	2.0,0.0
5.0,0.5	4.0,0.5	8.5,0.5	6.0,0.5	4.0,0.5	3.0,0.5
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5.6,0.0	5.2,0.0	4.3,0.0	3.9,0.0	3.5,0.0	3.1,0.0
5.5,0.5	4.0,0.5	7.0,0.5	5.0,0.5	4.0,0.5	2.5,0.5
8.0,0.5	7.5,0.5	8.5,0.5	8.0,0.5	7.5,0.5	7.0,0.5
8.4,0.4	8.0,0.5	9.3,0.4	8.8,0.4	8.2,0.4	7.5,0.5
5.0,0.0	5.0,0.0	7.0,0.0	6.0,0.0	5.0,0.0	5.0,0.0
7.0,0.5	6.5,0.5	8.5,0.5	7.0,0.5	5.5,0.5	4.0,0.5
3.5,1.0	2.0,1.0	7.0,1.0	5.0,1.0	3.0,1.0	1.0,1.0
6.0,0.5	5.5,0.5	7.5,0.5	5.0,0.5	3.5,0.5	3.0,0.5
6.0,2.0	4.0,2.0	6.0,2.0	6.0,2.0	4.0,2.0	2.0,2.0
6.3,0.5	5.3,0.5	7.8,0.5	5.9,0.5	4.0,0.5	2.4,0.5

Table A32. (Continued)

<u>(7.00,2.00)</u>	<u>(7.00,4.00)</u>	<u>(7.00,6.00)</u>	<u>(7.00,8.00)</u>
7.0,0.0	5.0,0.0	2.0,0.0	1.0,0.0
7.0,0.0	5.0,0.0	3.0,0.0	2.0,0.0
8.0,0.9	5.0,0.9	4.0,0.9	2.0,0.9
9.0,0.5	8.5,0.5	8.0,0.5	7.5,0.5
6.5,0.5	6.0,1.0	5.5,1.0	5.0,1.0
7.5,0.5	5.5,0.5	3.5,0.5	1.5,0.5
6.0,0.0	4.0,0.0	2.0,0.0	2.0,0.0
8.0,0.5	4.0,0.5	3.0,0.5	1.0,0.5
8.0,0.0	--	--	3.0,0.0
2.3,0.0	1.9,0.0	1.4,0.0	1.0,0.0
5.5,0.5	4.0,0.5	2.5,0.5	1.0,0.5
8.0,0.5	7.5,0.5	7.0,1.5	6.5,0.5
9.2,0.5	8.7,0.4	8.0,0.4	7.0,0.4
7.0,0.0	6.0,0.0	5.0,0.0	5.0,0.0
8.0,0.5	6.0,0.5	4.0,0.5	2.0,0.5
7.0,1.0	4.0,1.0	2.0,1.0	0.0,1.0
7.0,0.5	4.0,0.5	2.5,0.5	2.0,0.5
6.0,2.0	4.0,2.0	2.0,2.0	0.0,2.0
7.0,0.5	4.0,1.0	1.8,0.5	0.3,0.5

APPENDIX B

Appendix B π curve

The π curve is a smooth bell shaped curve, symmetrical around a central value. The following equations are used to develop a π curve (Figure B1).

$$f(x) = 2 \left[\frac{x-(a-c)}{c} \right]^2 \quad \text{if } a-c \leq x \leq a-\frac{c}{2}$$

$$f(x) = 1 - 2 \left[\frac{x-a}{c} \right]^2 \quad \text{if } a-\frac{c}{2} \leq x \leq a$$

where $f(x)$ is the membership value, a is the central value and c is the range of variation (i.e., the points having null membership are located at $a \pm c$).

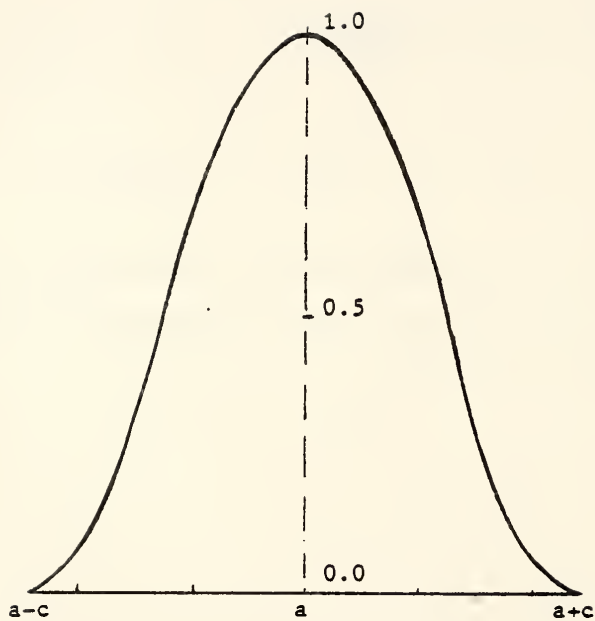


Figure B1. Typical π curve.

APPENDIX C

Appendix C

Fuzzy Pavement Condition Rating (PCR)

The parametric study presented in this appendix was performed to compare two methods to obtain the fuzzy PCR.

In this example, it is considered that only two types of distress, called 1 and 2 showed rating different from 0 (all the other ratings were null). It was assumed that the experts suggested a range of variation equal to ± 1.0 for distress 1 and ± 1.5 for distress 2. It was also assumed that the distress ratings (central values) of a given pavement section were 3 and 5 for distress 1 and 2, respectively.

In the first method, using the suggested ranges the fuzzy distress rating was obtained for each distress type by fitting a π curve to the assumed central value and range (Figure C1 and C2). Then, the fuzzy PCR was formed using the following equation (Gunaratne, 1984):

$$\mu_{\text{PCR}}(y) = \sup_{y=100-\sum_j x_j} \min_i [\mu_{\theta_i}(x_j)]$$

where $0 \leq x_j \leq 10$, i is the distress type, and y is any value supporting the PCR of the section. It follows that $0 \leq y \leq 100$ and therefore, the PCR is a fuzzy set on the scale of 0-100.

In the second method, only one π curve was used to represent the global effect (summation) of the distress types. The π curve

has a membership of 1.0 for a distress rating of 8 ($5+3$) and a membership of 0.0 for ratings of 5.5 and 10.5 (8 ± 2.5 , where 2.5 is the sum of the assumed ranges). The fuzzy PCR is then obtained by subtracting this global distress rating from 100.

Both methods gave exactly the same result (Figure C3). The second method was used in this study for the development of fuzzy PCR because it is more efficient in terms of computing time.

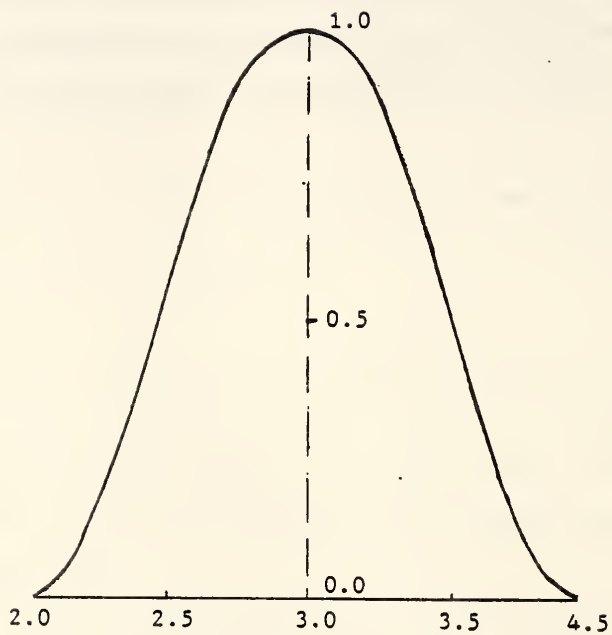


Figure C1. Fuzzy Distress Rating for Distress 1.

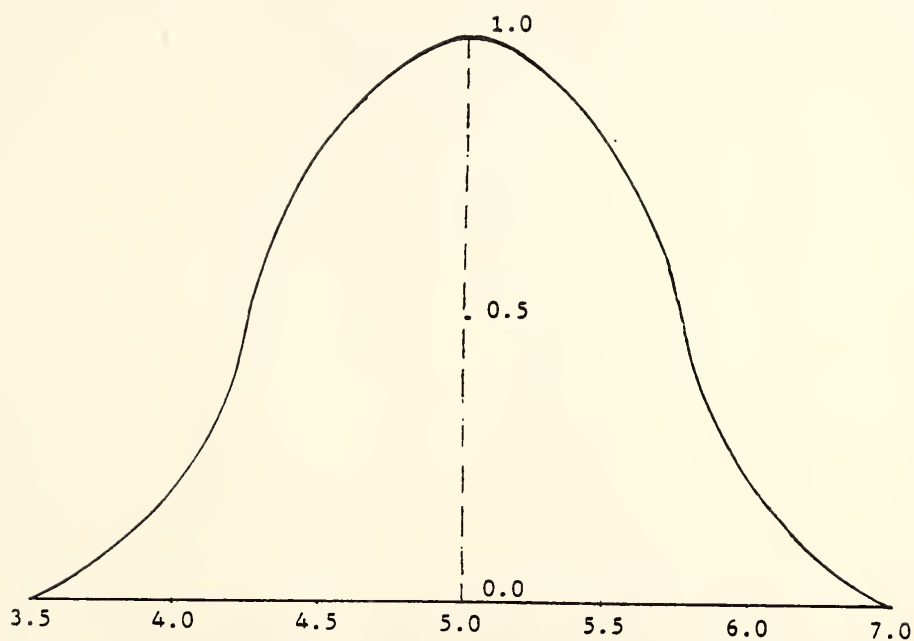


Figure C2. Fuzzy Distress Rating for Distress 2.

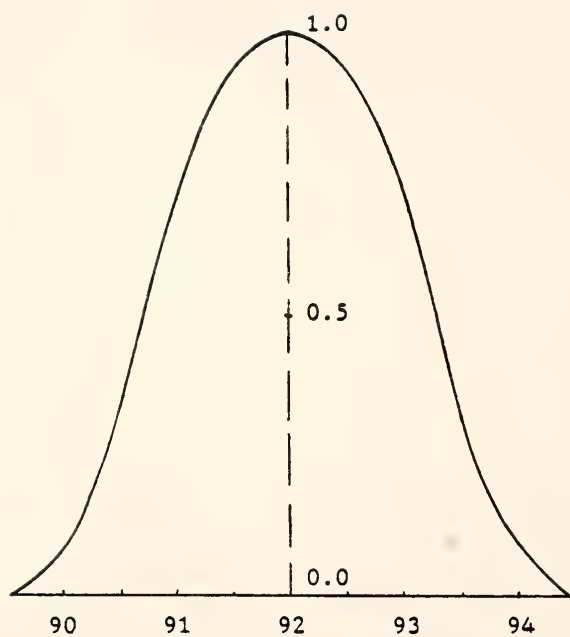


Figure C3. Fuzzy PCR Obtained Taking Into Account Distress 1 and 2.

APPENDIX D

Appendix D

Parametric studies for the RR and FN versus acceptability index relationship

Parametric studies were performed to show how the acceptability and nonacceptability indices vary as a function of RR and FN values. Indices were computed for RR values ranging from 0 to 3000 with increments of 100, and FN values from 0 to 100 with increments of 10.

These studies showed that:

a) Varying the ranges of variation to fuzzify the PSR and RR affected the acceptability relationship (Figure D1). Increasing the ranges of variation (ROV) for the PSR and RR improved the relation by making it smoother. This is a direct consequence of filling some of the gaps in the PSR-RR matrix (Chapter 1).

b) Including more RR-PSR pairs obtained from IDOH data (Summary of pavement roughness, 1983) improved the relationship (Figure D2). Most gaps were filled and the irregularities that were present in the original acceptability index versus RR curve disappeared.

c) Fuzzy PSI's were obtained by combining the PSR-RR matrix with fuzzy RR's. The procedure was repeated for RR values ranging from 0 to 3000 with a step of 100. The relationship between RR and central PSI is shown in Figure D3. The width of all the fuzzy PSI's was determined at a value of membership 0.5 and plot-

ted against the central PSI value with membership of 1.0 (Figure D4). The plot shows a clear trend between the width of the fuzzy sets and the central value.

Linear regressions were used to correlate central PSI with RR and width of the central PSI. Based on these relationships, fuzzy PSI's are readily obtained according to the following procedure: Measure the RR; determine the central PSI "c" from Figure D3; enter Figure D4 and determine the width of the fuzzy PSI, "w"; fit a π curve through "c", at a membership of 1.0 and through " $c \pm \frac{w}{2}$ " at a membership 0.5. Figures D3 and D4 were obtained using information from asphalt sections, but the same procedure was followed for pavements in other categories (Figures D5 to D10).

The suggested method to obtain PSI's resulted in perfectly smooth acceptability or nonacceptability index versus RR relationships. This improvement is illustrated by comparing the curves in Figure D11, obtained directly from the PSR-RR matrix, to the curves in Figure D12, obtained with the regression equation. Similar improvements are shown in Figures D13 to D19.

d) Finally, the relationships between the acceptability and nonacceptability indices and the Friction Number were developed (Figure D19). Smooth relationships were obtained.

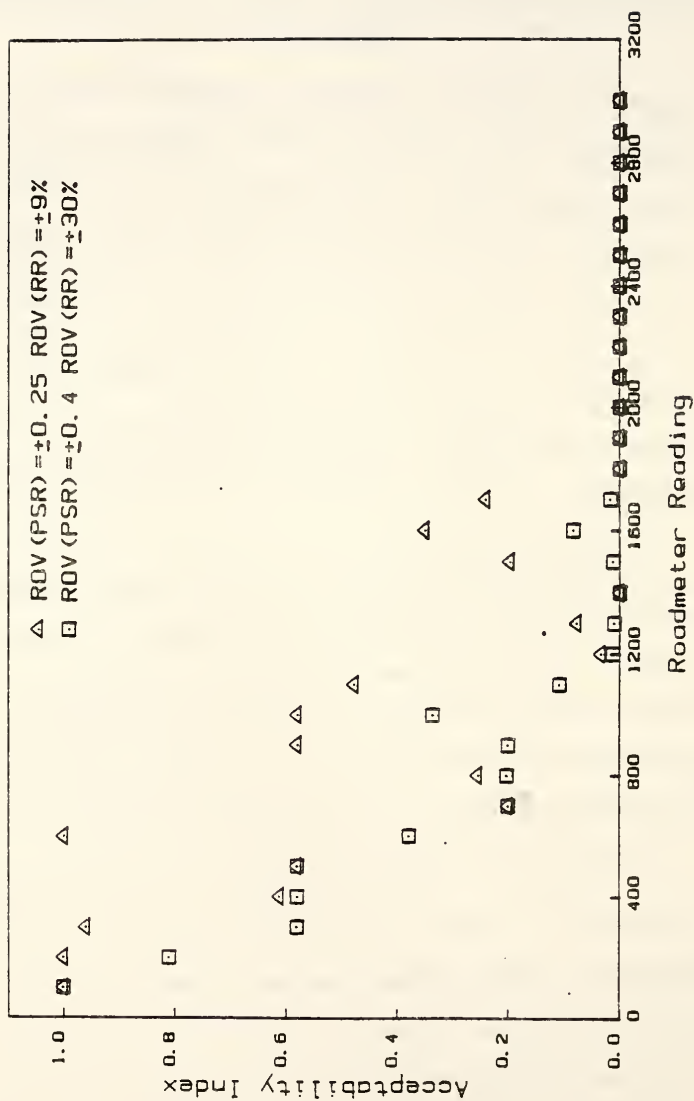


Figure D1. Range of Variation Effect on Acceptability Index vs. RR Relationship.

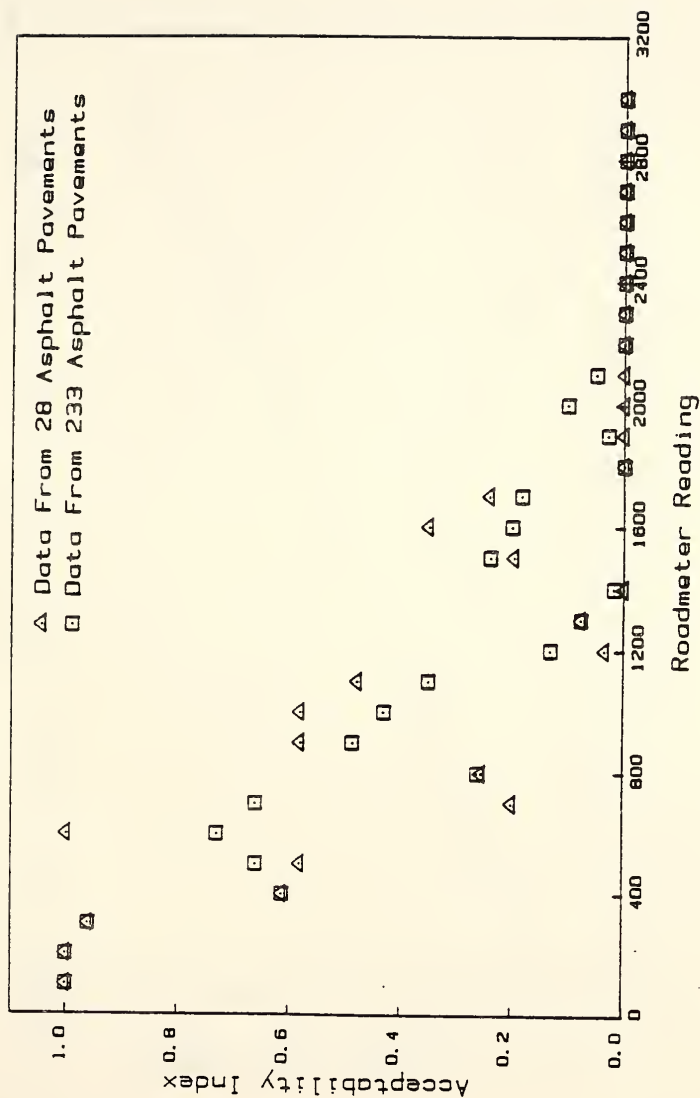


Figure D2. Variable Number of Sections Effect on Acceptability vs. RR Relationship.

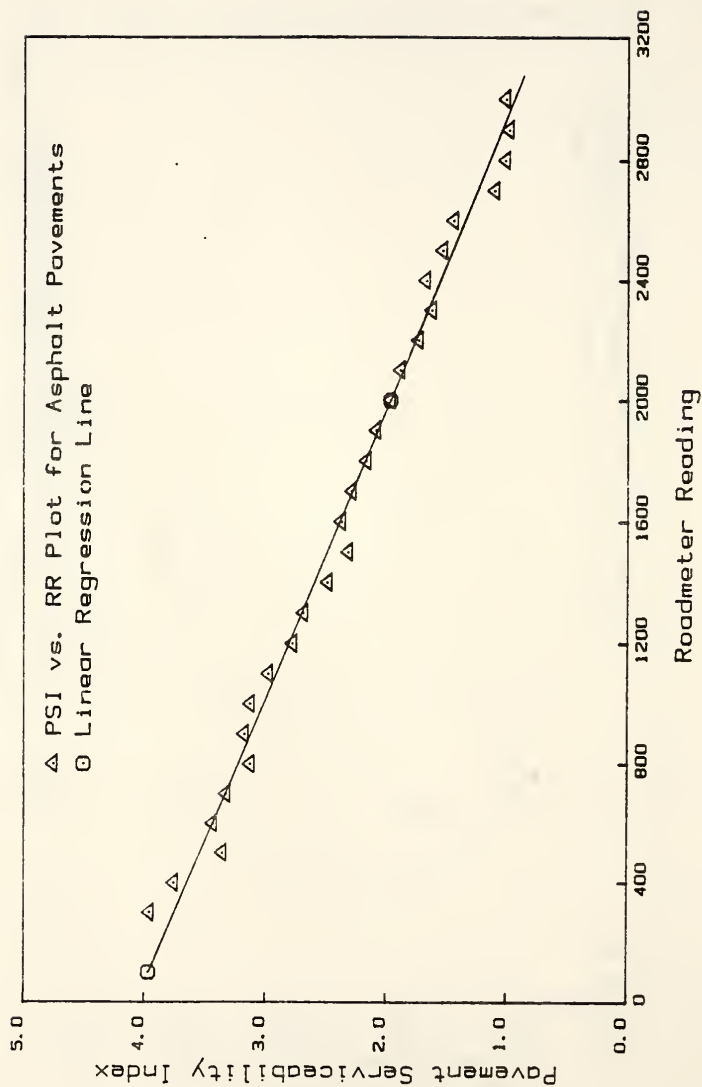


Figure D3. Relationship Between Central PSI and RR.

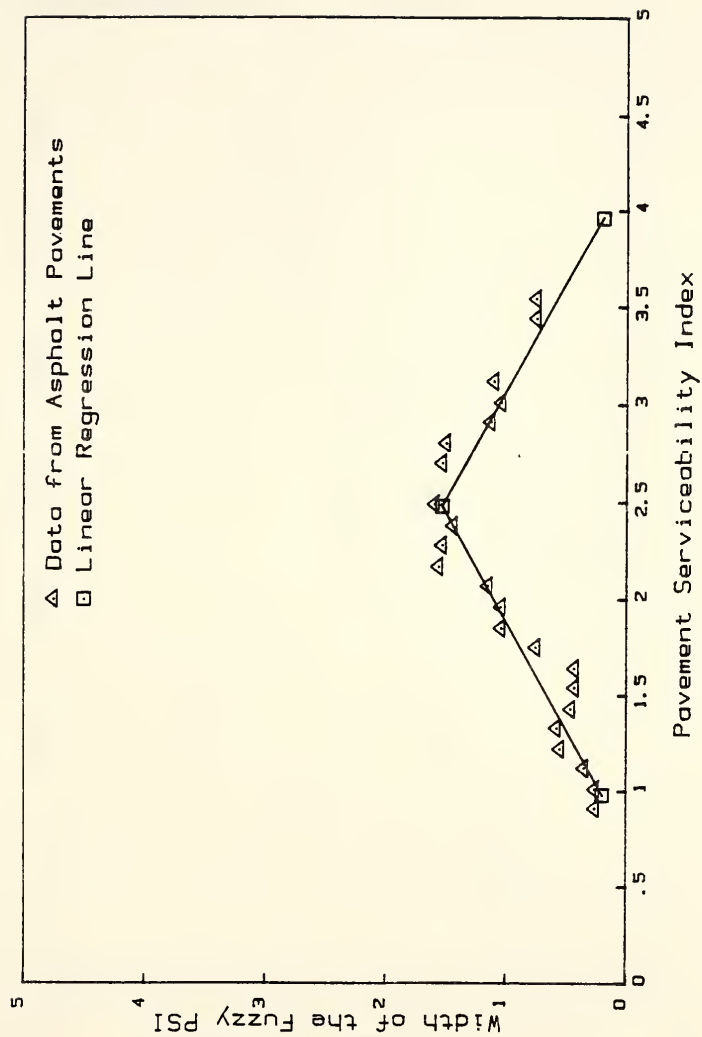


Figure D4. Relationship Between Width of Fuzzy PSI and Central PSI.

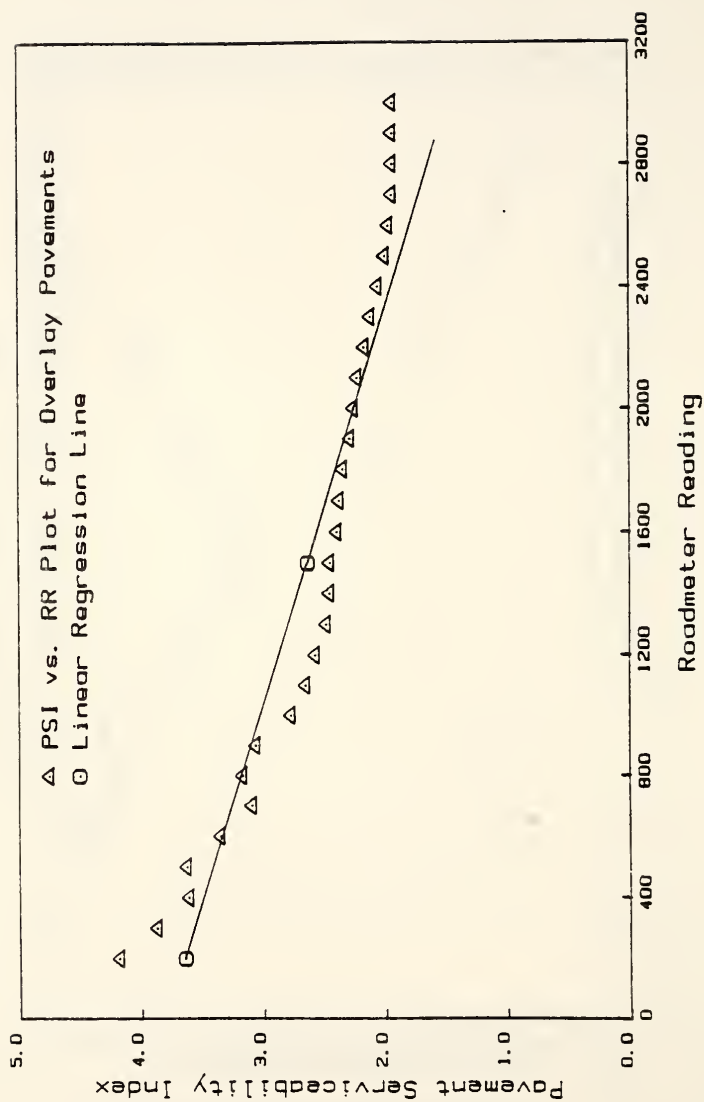


Figure D5. Relationship Between Central PSI and RR.

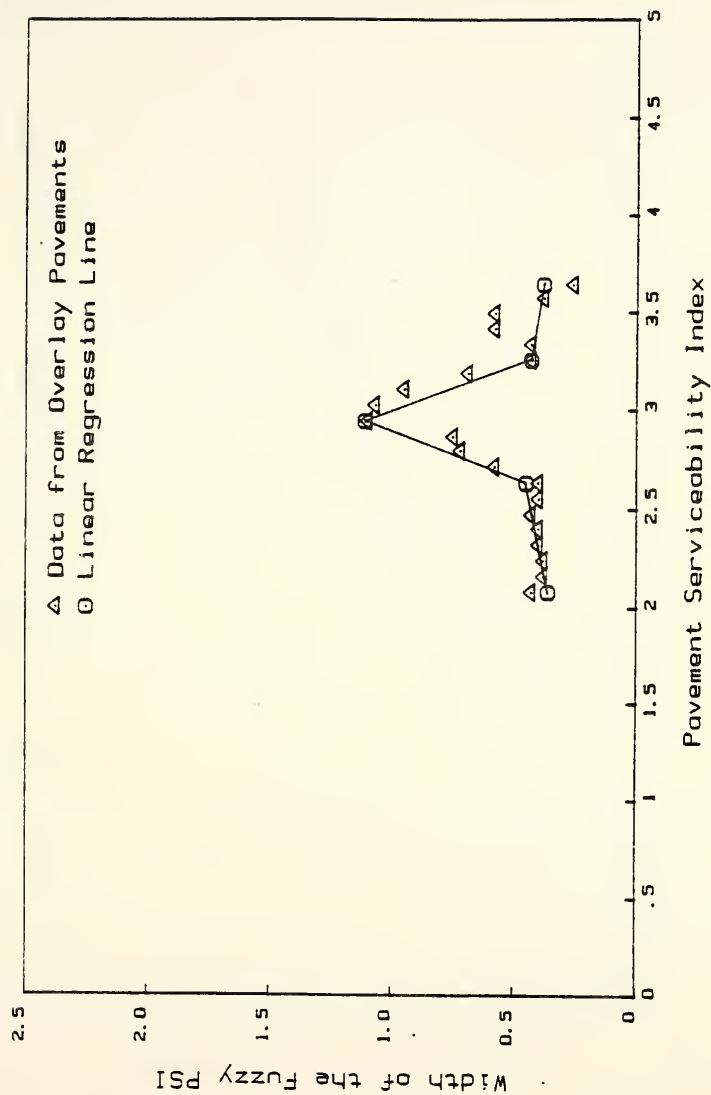


Figure D6. Relationship Between Width of Fuzzy PSI and Central PSI.

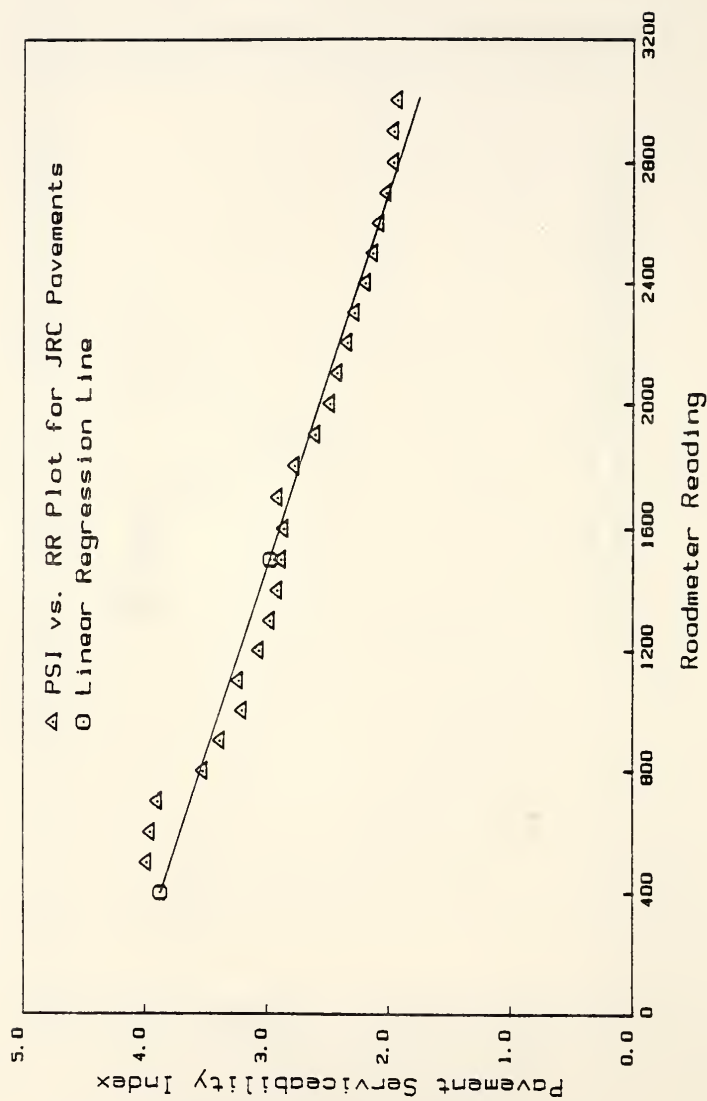


Figure D7. Relationship Between Central PSI and RR.

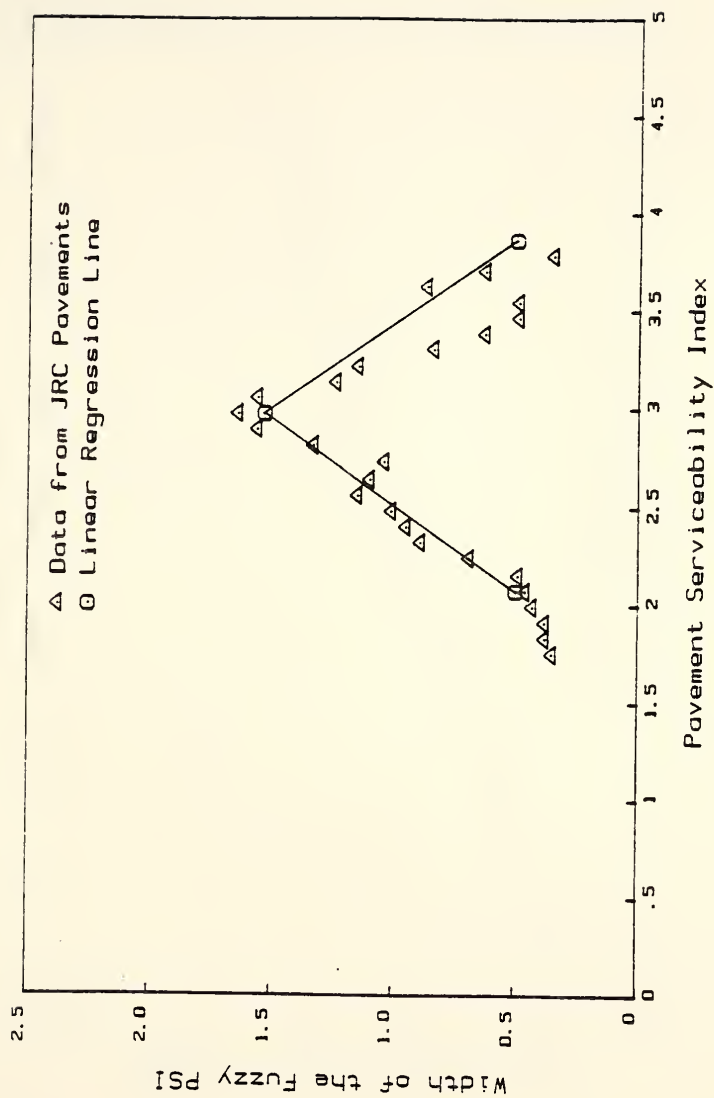


Figure D8. Relationship Between Width of Fuzzy PSI and Central PSI.

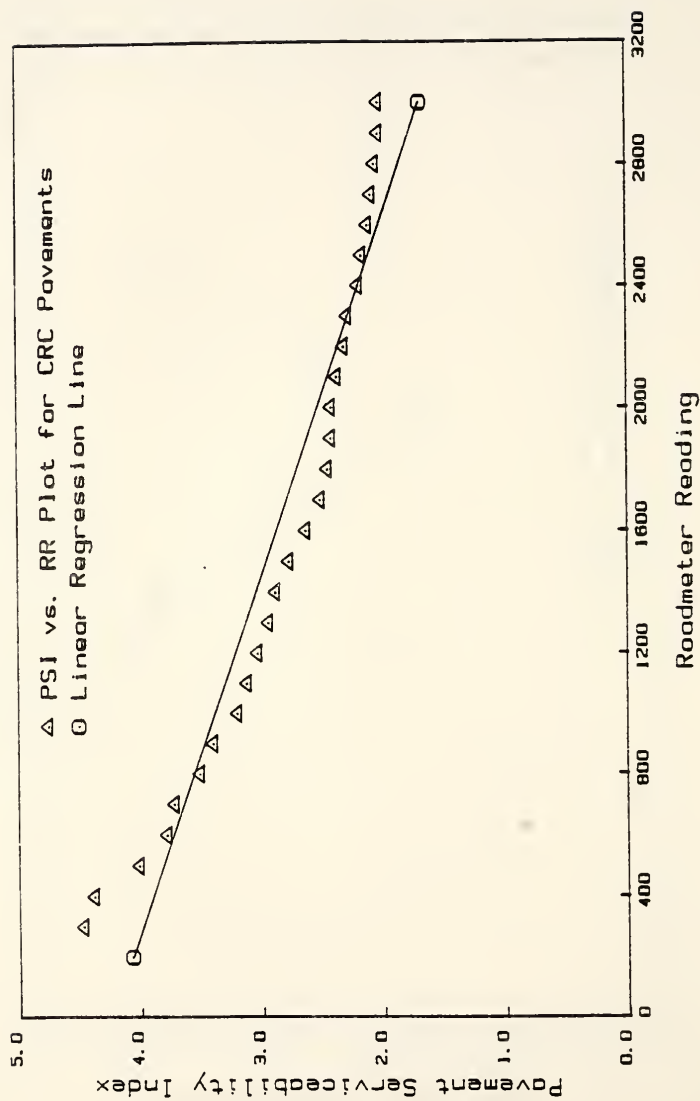


Figure D9. Relationship Between Central PSI and RR.

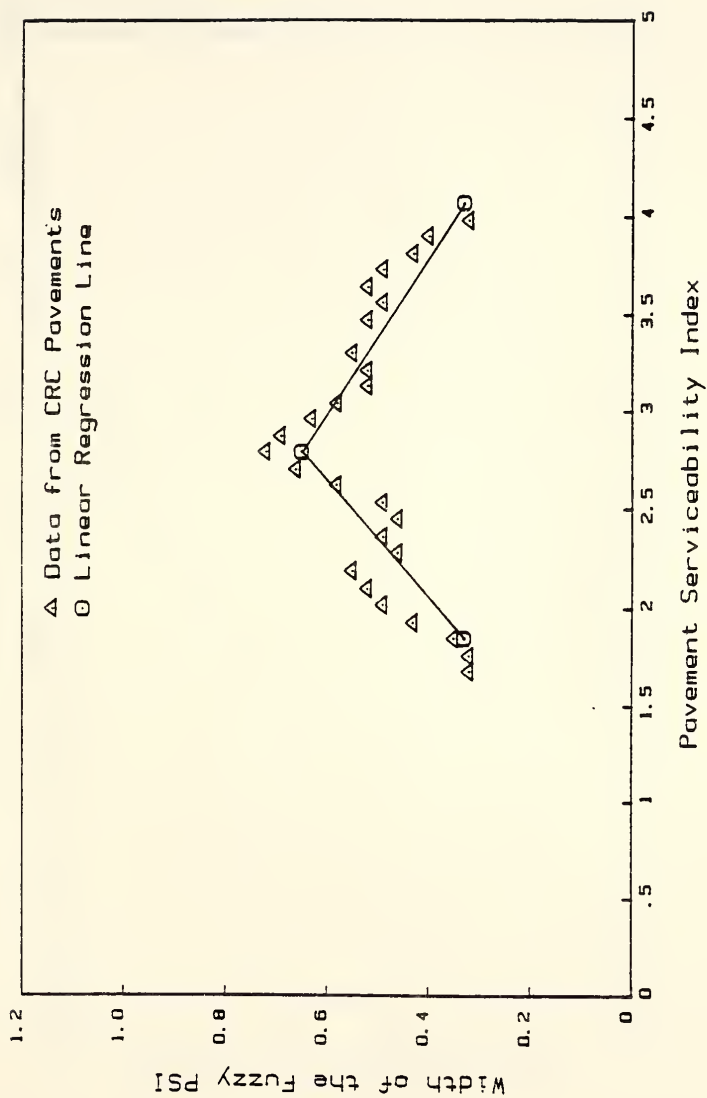


Figure D10. Relationship Between Width of Fuzzy PSI and Central PSI.

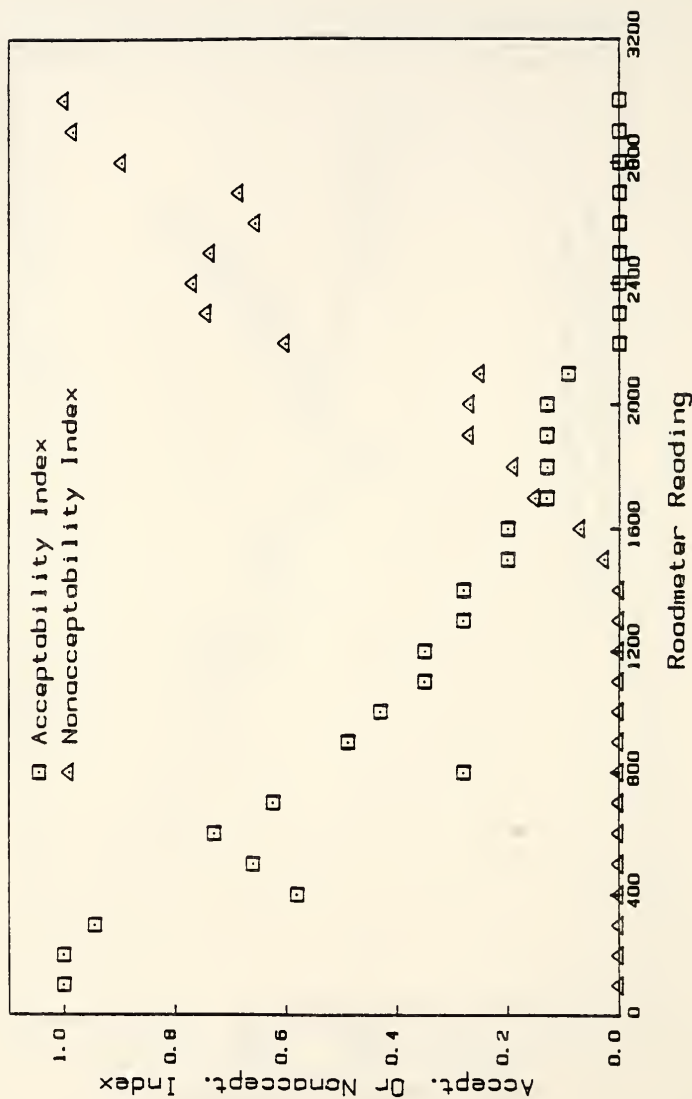


Figure D11. Acceptability and Nonacceptability Index vs. RR for Asphalt Pavements Using the PSR-RR matrix.

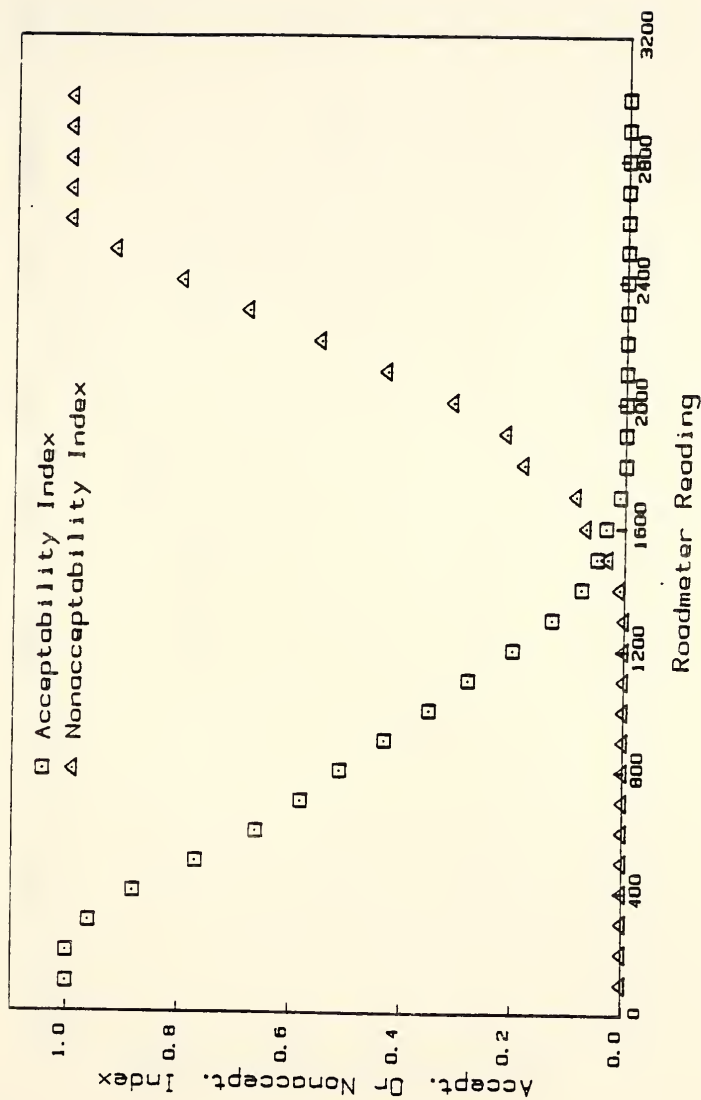


Figure D12. Acceptability and Nonacceptability Index vs. RR for Asphalt Pavements.
The Proposed Method to Develop Fuzzy PSI was Used.

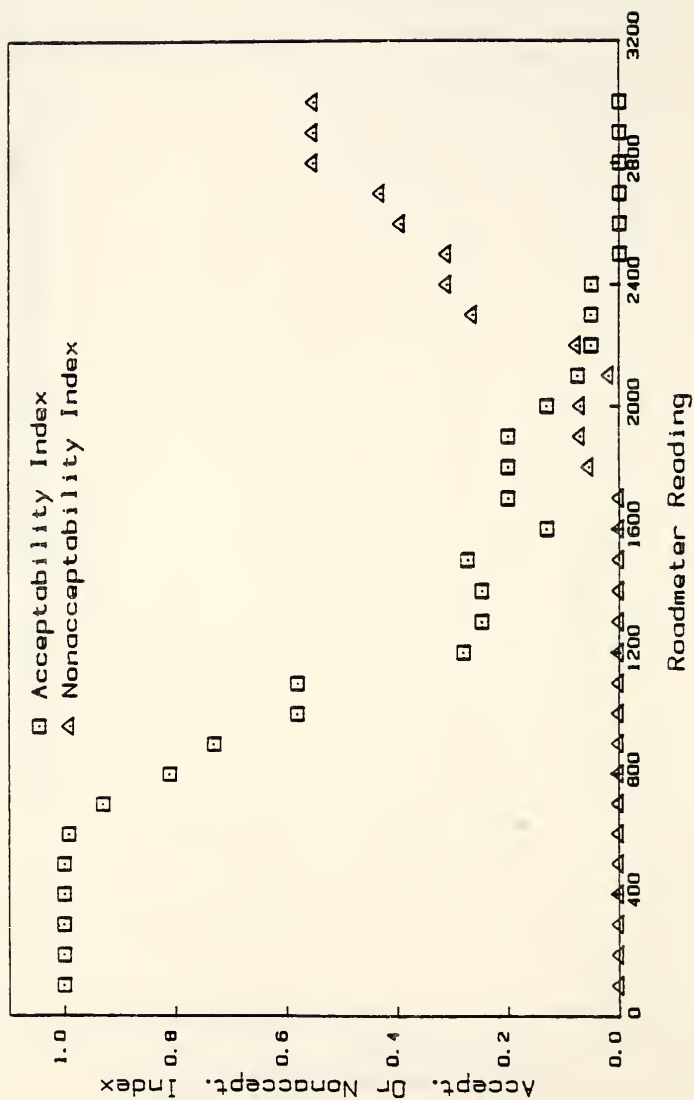


Figure D13. Acceptability and Nonacceptability Index vs. RR for Overlay Pavements Using the PSR-RR Matrix.

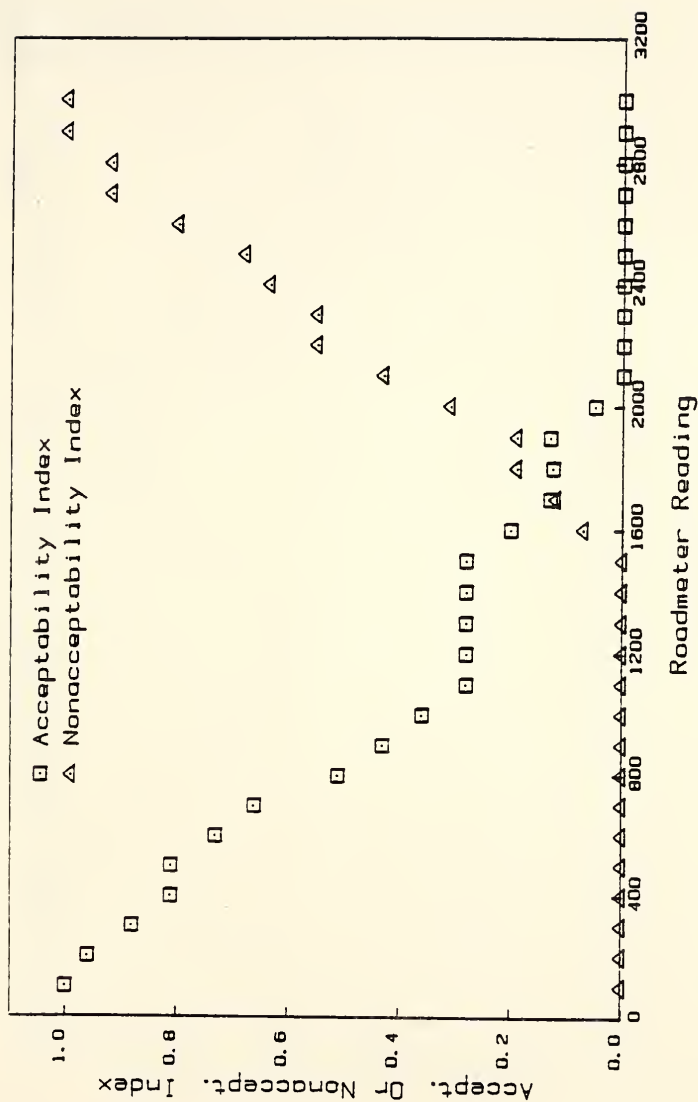


Figure D14. Acceptability and Nonacceptability Index vs. RR for Overlay Pavements.
The Proposed Method to Develop Fuzzy PSI was Used.

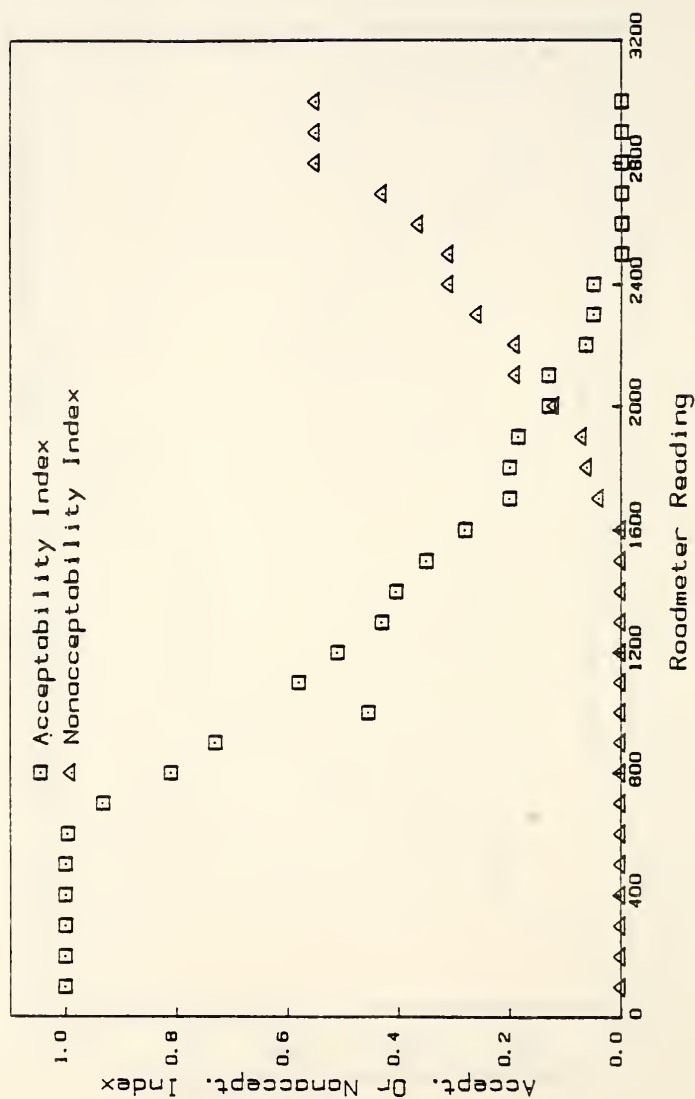


Figure D15. Acceptability and Nonacceptability Index vs. RR for JRC Pavements Using the PSR-RR Matrix.

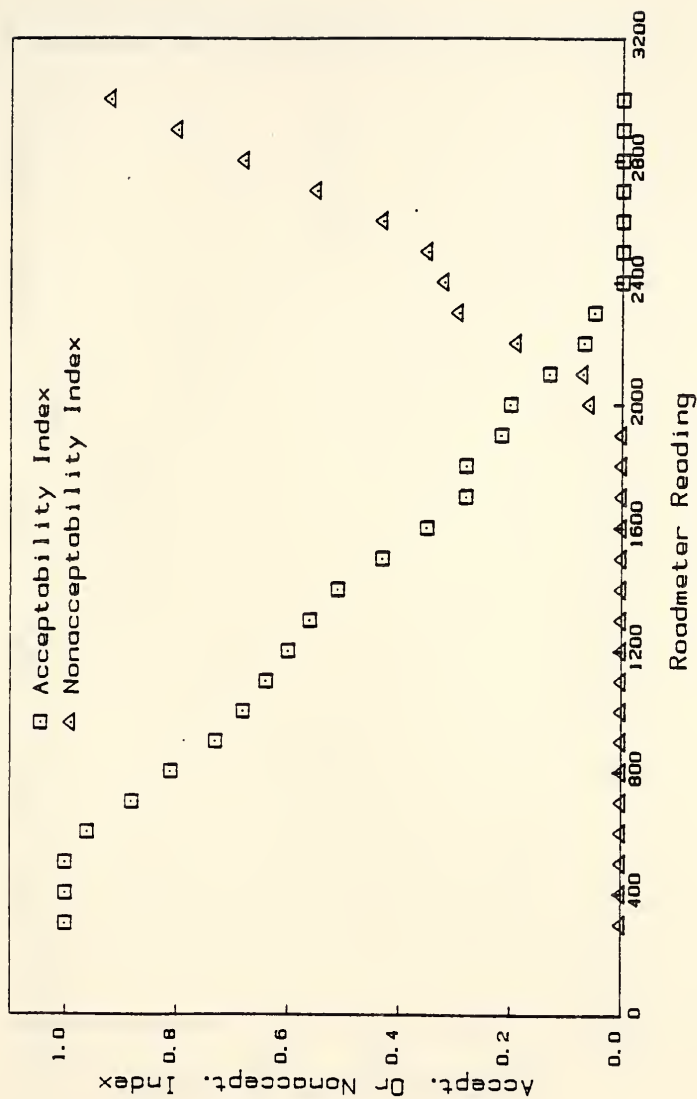


Figure D16. Acceptability and Nonacceptability Index vs. RR for JRC Pavements.
The Proposed Method to Develop Fuzzy PSI was Used.

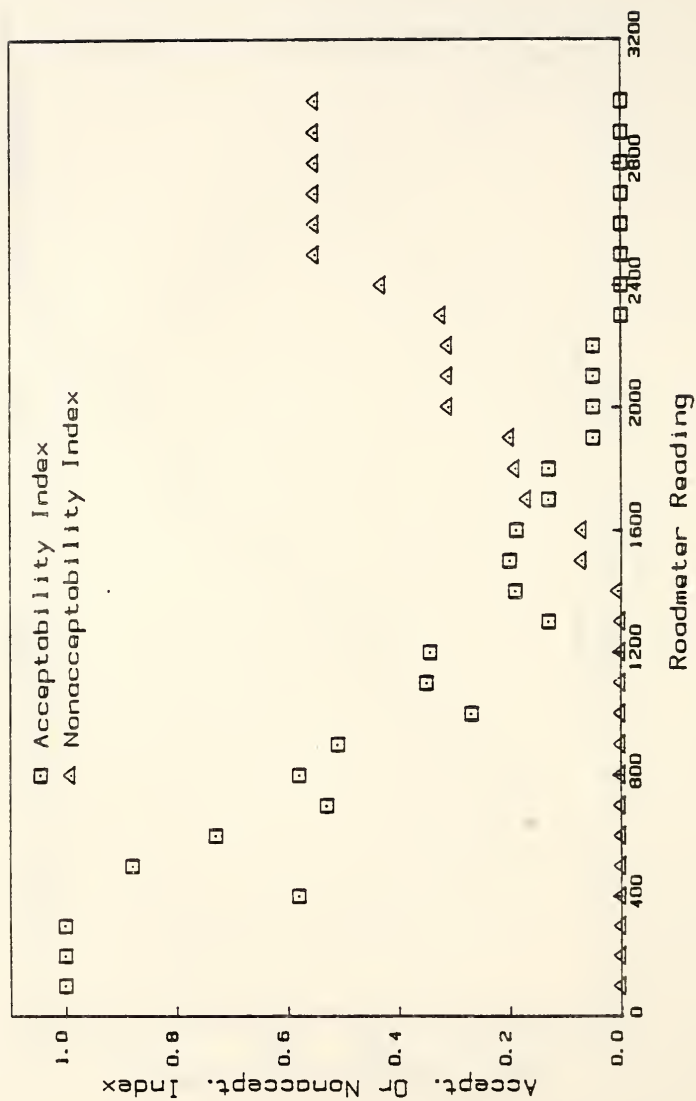


Figure D17. Acceptability and Nonacceptability Index vs. RR for CRC Pavements Using the PSR-RR Matrix.

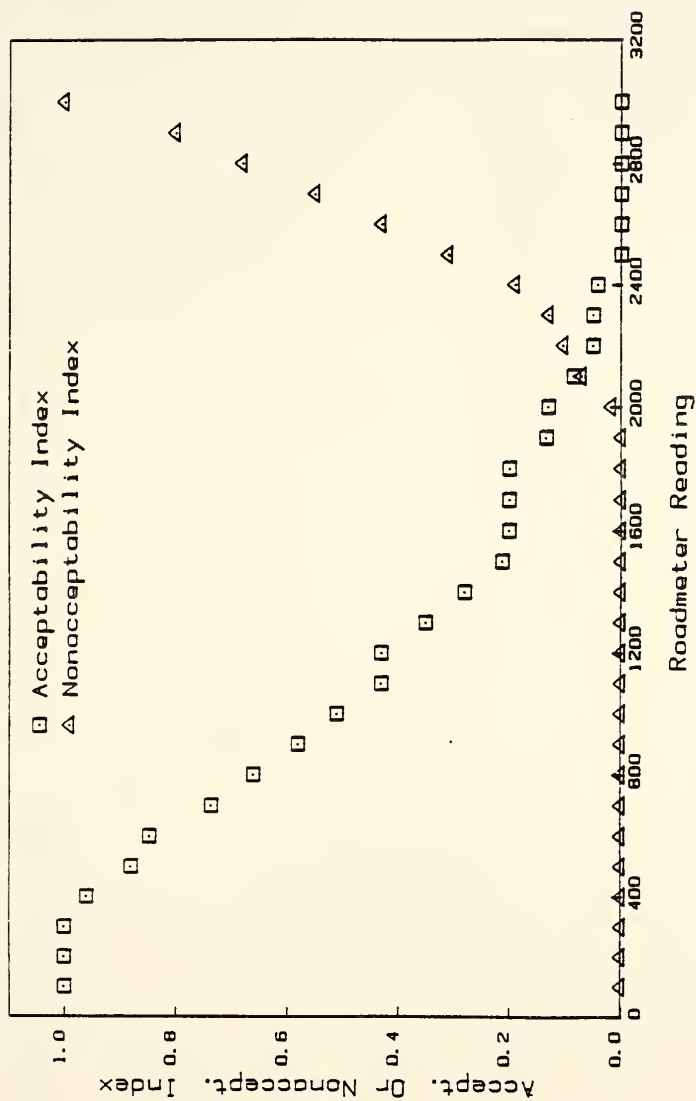


Figure D18. Acceptability and Nonacceptability Index vs. RR for CMV Pavements. The Proposed Method to Develop Fuzzy PSI was Used.

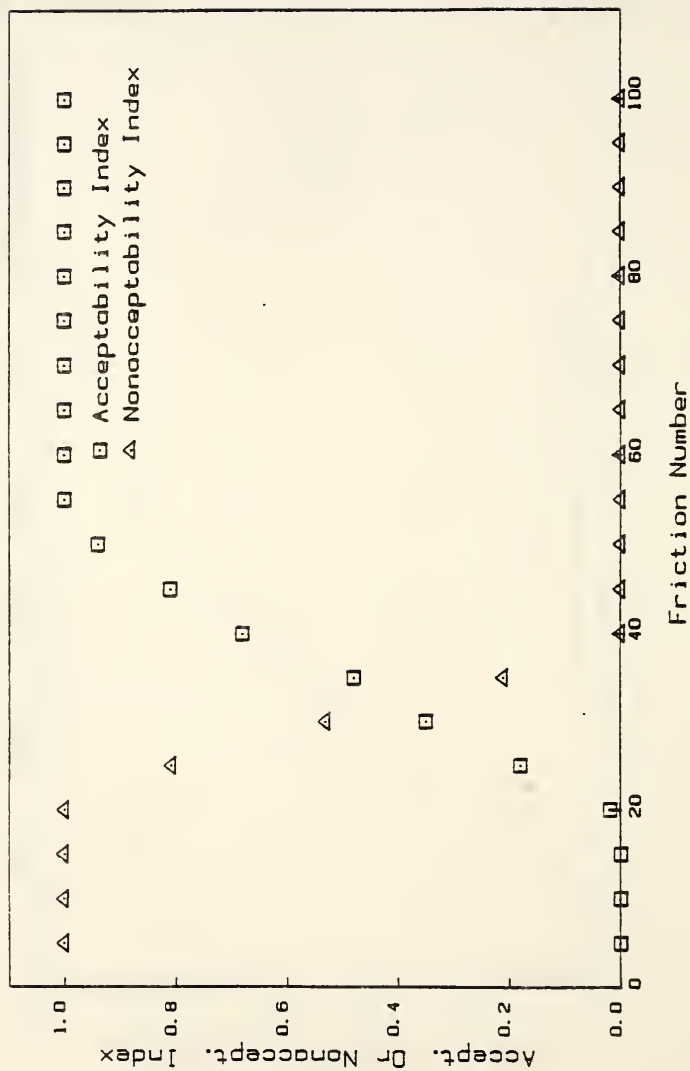


Figure D19. Acceptability and Nonacceptability Index vs. FN. for Flexible and Rigid Pavements.

APPENDIX E

Appendix E

Fuzzy PSI, FN, PCR for the data base

This appendix presents typical fuzzy sets for PSI, FN and PCR. The sets were computed with the computer programs Road.f, Skid.f and Dist.f using the data for asphalt pavement sections given in chapter 3. Similar sets were computed for the other types of pavements, but they are not reported here. The fuzzy sets are presented in a tabular form: the number in the left column gives a particular value of the parameter (PSI, FN or PCR) and the number in right column is the associated membership value (between 0.0 and 1.0).

1) Fuzzy PSI (Note: the Roadmeter Reading of each section is also given).

Section No. 1	
Fuzzy PSI	
1.20000	0.121039
1.30000	0.197886
1.40000	0.293526
1.50000	0.407960
1.60000	0.539558
1.70000	0.661716
1.80000	0.765081
1.90000	0.849652
2.00000	0.915429
2.10000	0.962413
2.20000	0.990603
2.30000	1.000000
2.40000	0.990603
2.50000	0.962413
2.60000	0.915429
2.70000	0.849652
2.80000	0.765081
2.90000	0.661716
3.00000	0.539558
3.10000	0.407960
3.20000	0.293526

3.30000 0.197886
3.40000 0.121039

Roadmeter reading= 1669.00

Section No. 2

Fuzzy PSI

2.40000 0.189845
2.50000 0.331198
2.60000 0.511498
2.70000 0.687359
2.80000 0.824139
2.90000 0.921840
3.00000 0.980460
3.10000 1.00000
3.20000 0.980460
3.30000 0.921840
3.40000 0.824139
3.50000 0.687359
3.60000 0.511498
3.70000 0.331198
3.80000 0.189845

Roadmeter reading= 895.00

Section No. 3

Fuzzy PSI

2.50000 0.105028
2.60000 0.230222
2.70000 0.403920
2.80000 0.611955
2.90000 0.781724
3.00000 0.902989
3.10000 0.975747
3.20000 1.00000
3.30000 0.975747
3.40000 0.902989
3.50000 0.781724
3.60000 0.611955
3.70000 0.403920
3.80000 0.230222
3.90000 0.105028

Roadmeter reading= 794.00

Section No. 4

Fuzzy PSI

1.10000 0.129834
1.20000 0.216889
1.30000 0.326158
1.40000 0.457640
1.50000 0.600155
1.60000 0.722330
1.70000 0.822291
1.80000 0.900039
1.90000 0.955573

2.00000	0.988893
2.10000	1.000000
2.20000	0.988893
2.30000	0.955573
2.40000	0.900039
2.50000	0.822291
2.60000	0.722330
2.70000	0.600155
2.80000	0.457640
2.90000	0.326158
3.00000	0.216889
3.10000	0.129834

Roadmeter reading= 1783.00

Section No. 5

Fuzzy PSI

1.20000	0.125222
1.30000	0.202736
1.40000	0.298834
1.50000	0.413516
1.60000	0.544691
1.70000	0.665487
1.80000	0.767699
1.90000	0.851328
2.00000	0.916372
2.10000	0.962832
2.20000	0.990708
2.30000	1.000000
2.40000	0.990708
2.50000	0.962832
2.60000	0.916372
2.70000	0.851328
2.80000	0.767699
2.90000	0.665487
3.00000	0.544691
3.10000	0.413516
3.20000	0.298834
3.30000	0.202736
3.40000	0.125222

Roadmeter reading= 1661.00

Section No. 6

Fuzzy PSI

1.20000	0.125222
1.30000	0.202736
1.40000	0.298834
1.50000	0.413516
1.60000	0.544691
1.70000	0.665487
1.80000	0.767699
1.90000	0.851328
2.00000	0.916372
2.10000	0.962832

2.20000	0.990708
2.30000	1.000000
2.40000	0.990708
2.50000	0.962832
2.60000	0.916372
2.70000	0.851328
2.80000	0.767699
2.90000	0.665487
3.00000	0.544691
3.10000	0.413516
3.20000	0.298834
3.30000	0.202736
3.40000	0.125222

Roadmeter reading= 1661.00

Section No. 7

Fuzzy PSI

2.60000	0.191841
2.70000	0.360839
2.80000	0.576444
2.90000	0.761750
3.00000	0.894111
3.10000	0.973528
3.20000	1.000000
3.30000	0.973528
3.40000	0.894111
3.50000	0.761750
3.60000	0.576444
3.70000	0.360839
3.80000	0.191841

Roadmeter reading= 756.00

Section No. 8

Fuzzy PSI

2.60000	0.191841
2.70000	0.360839
2.80000	0.576444
2.90000	0.761750
3.00000	0.894111
3.10000	0.973528
3.20000	1.000000
3.30000	0.973528
3.40000	0.894111
3.50000	0.761750
3.60000	0.576444
3.70000	0.360839
3.80000	0.191841

Roadmeter reading= 756.00

Section No. 9

Fuzzy PSI

1.30000	0.100626
1.40000	0.166980

1.50000	0.250048
1.60000	0.349831
1.70000	0.466327
1.80000	0.590508
1.90000	0.699149
2.00000	0.791076
2.10000	0.866288
2.20000	0.924787
2.30000	0.966572
2.40000	0.991643
2.50000	1.000000
2.60000	0.991643
2.70000	0.966572
2.80000	0.924787
2.90000	0.866288
3.00000	0.791076
3.10000	0.699149
3.20000	0.590508
3.30000	0.466327
3.40000	0.349831
3.50000	0.250048
3.60000	0.166980
3.70000	0.100626

Roadmeter reading= 1417.00

Section No. 10

Fuzzy PSI

The normalized fuzzy PSI

1.20000	0.163212
1.30000	0.245851
1.40000	0.345358
1.50000	0.461733
1.60000	0.586723
1.70000	0.696368
1.80000	0.789144
1.90000	0.865052
2.00000	0.924092
2.10000	0.966263
2.20000	0.991566
2.30000	1.000000
2.40000	0.991566
2.50000	0.966263
2.60000	0.924092
2.70000	0.865052
2.80000	0.789144
2.90000	0.696368
3.00000	0.586723
3.10000	0.461733
3.20000	0.345358
3.30000	0.245851
3.40000	0.163212

Roadmeter reading= 1590.00

2) Fuzzy Friction Number for the asphalt sections included
in the data base (chapter 3).

pavement section no : 1

FN	membership
67.000	0.117
66.000	0.466
65.000	0.848
64.000	0.998
63.000	0.914
62.000	0.598
61.000	0.193
60.000	0.013
Central friction number=	63.80

pavement section no : 2

FN	membership
39.000	0.059
38.000	0.658
37.000	1.000
36.000	0.658
35.000	0.059
Central friction number=	37.00

pavement section no : 3

FN	membership
60.000	0.086
59.000	0.402
58.000	0.848
57.000	1.000
56.000	0.848
55.000	0.402
54.000	0.086
Central friction number=	57.00

pavement section no : 4

FN	membership
45.000	0.023
44.000	0.402
43.000	0.941
42.000	0.941
41.000	0.402
40.000	0.023
Central friction number=	42.50

pavement section no : 5

FN	membership
45.000	0.023
44.000	0.402
43.000	0.941
42.000	0.941
41.000	0.402
40.000	0.023
Central friction number=	42.50

pavement section no : 6

FN	membership
45.000	0.023
44.000	0.402
43.000	0.941
42.000	0.941
41.000	0.402
40.000	0.023
Central friction number=	42.50

pavement section no : 7

FN	membership
55.000	0.023
54.000	0.342
53.000	0.807
52.000	1.000
51.000	0.807
50.000	0.342
49.000	0.023
Central friction number=	52.00

pavement section no : 8

FN	membership
55.000	0.023
54.000	0.342
53.000	0.807
52.000	1.000
51.000	0.807
50.000	0.342
49.000	0.023
Central friction number=	52.00

pavement section no : 9

FN	membership
43.000	0.288
42.000	0.848
41.000	0.979
40.000	0.534
39.000	0.038
Central friction number=	41.30

pavement section no : 10

FN	membership
43.000	0.086
42.000	0.658
41.000	0.998
40.000	0.762
39.000	0.152
Central friction number=	40.90

3) Fuzzy PCR for asphalt pavement sections with nonacceptable roughness.

pavement section no. 1

PCR	membership
80.00	0.006

81.00	0.037
82.00	0.126
83.00	0.370
84.00	0.608
85.00	0.814
86.00	0.952
87.00	1.000
88.00	0.952
89.00	0.814
90.00	0.608
91.00	0.370
92.00	0.126
93.00	0.037
94.00	0.006

pavement section no. 4

PCR	membership
71.00	0.006
72.00	0.037
73.00	0.126
74.00	0.370
75.00	0.608
76.00	0.814
77.00	0.952
78.00	1.000
79.00	0.952
80.00	0.814
81.00	0.608
82.00	0.370
83.00	0.126
84.00	0.037
85.00	0.006

pavement section no. 5

PCR	membership
72.00	0.006
73.00	0.037
74.00	0.126
75.00	0.370
76.00	0.607
77.00	0.814
78.00	0.952
79.00	1.000

80.00	0.952
81.00	0.814
82.00	0.607
83.00	0.370
84.00	0.126
85.00	0.037
86.00	0.006

pavement section no. 6

PCR	membership
74.00	0.006
75.00	0.037
76.00	0.126
77.00	0.370
78.00	0.608
79.00	0.814
80.00	0.952
81.00	1.000
82.00	0.952
83.00	0.814
84.00	0.608
85.00	0.370
86.00	0.126
87.00	0.037
88.00	0.006

pavement section no. 10

PCR	membership
84.00	0.007
85.00	0.038
86.00	0.127
87.00	0.371
88.00	0.609
89.00	0.814
90.00	0.952
91.00	1.000
92.00	0.952
93.00	0.814
94.00	0.609
95.00	0.371
96.00	0.127
97.00	0.038
98.00	0.007

APPENDIX F

Appendix F

Computer programs

This appendix contains the computer programs developed during this study:

Road.f

```

c    MODIFIED PROGRAM TO TAKE INTO ACCOUNT ALL THE FACTORS
c    FOR RR, PLOTTING 0.1 , 4.9.
c
c    This program can be used to ;
c        i. form a technical PSR out of panel ratings
c        ii. fuzzify a road-meter reading
c        iii. formulate a fuzzy relationship - PSR Vs.Road-meter
c        iv. compose an equivalent PSR out of a road-meter reading
c    implicit real(a-z)
c
c    dimension must(50),mx(50),mu(55),mus(120),accp(50)
c    dimension mupr(50,120),z(120),ck(205)
c
c    integer i,j,k,l,m,n,nn,b1,b2,l1,np,nacc,nnn,jk
c
c    open (unit = 3 , file = 'memb' , status = 'old')
c    open (unit = 4 , file = 'psi' , status = 'old')
c    open (unit = 1 , file = 'accep' , status = 'old')
c    open (unit = 2 , file = 'rr' , status = 'old')
c
c    Formation of a fuzzy technical PSR out of panel ratings
c
c        do 15 i=1,50
c        do 10 j=1,120
c        mupr(i,j)=0.0
c        accp(i)=0.0
10    continue
15    continue
c
c        read *,ns,b
c        print *,'Number of input sections=',ns,'b=',b
c        do 2500 l1=1,ns
c
c            do 16 l=1,50
c            must(l)=0.0
c            mx(l)=0.0
16        continue
c            do 18 l=1,55
c            mu(l)=0.0
18        continue
c
c        read *, ngrp
c
c        do 300 nn=1,ngrp
c

```

```

      read *, nsub,alpha
c
      do 200 n=1,nsub
      read *, nurat,w
c
      do 100 M=1,nurat
      read *, p
      b1=10*b
c
      do 50 i=1,b1
      x=p-(i-1)/10.0
      b2=0.5*b1
      if ((i-1).gt. b2) go to 20
      mx(i)=1-2*(((i-1)/10.0/b)**2)
      go to 30
20      mx(i)=2*(((i-1)/10.0-b)/b)**2)
30      continue
c
      j=10.0*x
      k=10.0*(x+(i-1)/5.0)
c
      mx(i)=w*mx(i)
      if (j.lt. 0.0) go to 40
      if (mx(i).lt. mu(j)) go to 40
      mu(j)=mx(i)
c
40      if (mx(i).lt. mu(k)) go to 50
      mu(k)=mx(i)
50      continue
c
c
100      continue
200      continue
c
c
      do 280 l=1,50
      mu(l)=mu(l)**alpha
      if (nn.gt. 1)go to 260
      must(l)=mu(l)
      go to 270
260      must(l)=must(l)*mu(l)
270      mu(l)=0.0
280      continue
c
300      continue
c
c      normalize psr for combination with rr
c
      maxmust=0.0
      do 400 l=1,50
      if (maxmust.gt. must(l)) go to 400
      maxmust=must(l)
400      continue

```

```

c
    if (maxmust. eq. 0.0) go to 500
    do 450 l=1,50
    must(l)=must(l)/maxmust
    if (must(l).lt.0.001) go to 450
c    print *, 'PSR', 1/10.0, 'MEMB', must(l)
450    continue
c
500    continue
c
c    Fuzzification of the roadmeter reading
c
c
    do 600 l=1,120
    mus(l)=0.0
600    continue
c
    call meter (mus,z,ll,ck,x,rint)
c
    do 700 j=1,120
    if (mus(j) .ge. 0.01) then
c    print *, z(j),mus(j)
    endif
700    continue
c
c    Formulation of the PSR-Roadmeter relationship
c
c
    do 2400 i=1,50
    do 2300 j=1,120
    if (must(i). gt. mus(j)) go to 2200
    if (mupr(i,j). gt. must(i)) go to 2250
    mupr(i,j)=must(i)
    go to 2250
2200    if (mupr(i,j). gt. mus(j)) go to 2250
    mupr(i,j)=mus(j)
2250    ii=i/10.0
2300    continue
c
2400    continue
c
2500    continue
c
    write(6,33)
33    format(6x,"0.1  0.3  0.5  0.7  0.9  1.1
* 1.3  1.5  1.7  1.9  2.1
* 2.3  2.5  2.7  2.9  3.1  3.3
* 3.5  3.7  3.9  4.1  4.3  4.5  4.7
* 4.9")
    do 77 j=35,55
    jk=121-j
    jj=25.0*j
    ii=i/10.0

```

```

        write(6,36)jj,(mupr(i,jk),i=25,35)
36      format(f5.0,1x,25f5.2)
77      continue
c
c   Input of acceptable PSI range
c
        read *,nacc
c
        do 2700 nnn=1,nacc
        read *, i,accp(i)
2700    continue
c
c
c   Composition
c
        read *,np
        do 7000 m=1,np
        write(6,6100) m
c
        call meter(mus,z,ll,ck,x,rnt)
c
        do 3600 n=1,50
        must(n)=0.0
3600    continue
        do 4450 I=1,50
            do 4400 J=1,120
                if (mus(j). gt. mupr(i,j)) go to 4200
                if (must(i). gt. mus(j)) go to 4300
c
                must(i)=mus(j)
                go to 4300
c
4200        if (must(i). gt. mupr(i,j)) go to 4300
            must(i)=mupr(i,j)
4300        continue
4400        continue
c
4450    continue
c
c   normalize psi for comparison
c
        maxmust=0.0
        do 4800 i=1,50
        if (maxmust. gt. must(i)) go to 4800
        maxmust=must(i)
4800    continue
c
c
        write(6,6300)
c
        do 4900 i=1,50
        ii=i/10.0
        if (maxmust. eq. 0.0) go to 4810

```

```

        must(i)=must(i)/maxmust
        write(3,*) must(i)
        write(4,*) ii
4810    if (must(i). lt. 0.001) go to 4900
        write(6,4850) ii,must(i)
4850    format(f6.3,3x,f6.3)
4900    continue
5000    continue
c
c
c    Calculation of the comparison index
c
        truth=1.0
c
        do 6000 j=1,50
            must(j)=1.0-must(j)
            if (must(j). gt. accp(j)) go to 5500
            must(j)=accp(j)
5500    continue
c
        if (truth. lt. must(j)) go to 6000
        truth=must(j)
6000    continue
c
        write(6,6200)truth,x
17      format(f3.1,3x,f4.2)
6100    format(/,"pavement section no: ",i3,)
6200    format(2x,"index=",4x,f6.3,4x,
* "Roadmeter reading=",f10.2)
6300    format(2x,"PSI",5x,"membership",/)
c
        write(1,*) truth
        write(2,*) x
7000    continue
8000    continue
c
        close (unit = 3 , status = "keep")
        close (unit = 4 , status = "keep")
        close (unit = 1 , status = "keep")
        close (unit = 2 , status = "keep")
        stop
        end
c
c
c
c    subroutine meter(mu,z,ll,ck,x,rnt)
c
c
c    This subroutine is used to fuzzify the roadmeter reading for
c    i. imprecision of the measuring system.
c    ii. variations in the gas tank level.
c    iii. variations in the air temperature.
c    iv. variations in driver characteristics.

```

```

c
c
c
      implicit real(a-z)
      dimension k1(50),k2(200),ck(205),z(120),y(205),mu(120)
      integer i,j,k,m,n,ii,jj,kk,il,kk1,kk2,itr,ll
c
c  Read the input data : i. percent ranges of variation
c                      ii. number of intervals for discretization
c
      if (ll. gt. 1) go to 2200
c
      itr=1
      read *,r1,r2,n
c      print *,`r1=`,r1,`r2=`,r2,`n=`,n
      if (itr. eq. 1)go to 20
10      read *,r1
c      print *,`r1l=`,r1
      itr=itr+1
      go to 30
20      an=n-1
      rint=r1/an
c
30      continue
c
c  Initialization
c
      do 200 j=1,200
      k2(j)=0.0
200      continue
      do 100 i=1,n
      k1(i)=0.0
100      continue
c
c  Assigning of membership values to the kernels.
c
      do 500 i=1,50
      rrl=(i-1)*rint
c
      if (r1. ne. 0.0) go to 250
      k1(i)=1.0
      go to 600
250      if (rrl. gt. r1) go to 600
      if (rrl. gt. 0.5*r1)go to 300
      k1(i)=1-2*((rrl/r1)**2)
      go to 500
300      k1(i)=2*(((rrl-r1)/r1)**2)
500      continue
c
600      n=i
c
      if (itr. gt. 1)go to 1100
c

```

```

do 1000 j=1,50
rr2=(j-1)*rint
c
  if (r2. ne. 0.0) go to 750
  k2(j)=1.0
  go to 1200
750  if (rr2. gt. r2)go to 1200
  if (rr2. gt. 0.5*r2)go to 800
  k2(j)=1-2*((rr2/r2)**2)
  go to 1000
800  k2(j)=2*(((rr2-r2)/r2)**2)
1000  continue
  go to 1200
c
1100  continue
c
  do 1150 j=1,200
  if (ck(j). lt. 0.001)go to 1200
  k2(j)=ck(j)
1150  continue
c
c
1200  m=j
c
  do 1250 k=1,200
  ck(k)=0.0
  y(k)=0.0
1250  continue
c
  do 2000 i=1,n
  ii=i-1
  do 1800 j=1,m
  jj=j-1
  kk=ii+jj
  k=kk+1
  k12=k1(i)*k2(j)
  if (ck(k). gt. k12) go to 1300
  ck(k)=k12
1300  continue
c
  if (ii. gt. jj)go to 1400
  kk=jj-ii
  go to 1500
1400  kk=ii-jj
1500  continue
  if (ck(k). gt. k12)go to 1800
  ck(k)=k12
1800  continue
2000  continue
c
  if (itr. ne. 3)go to 10
c
2200  continue

```

```

c
c  Read input roadmeter readings
c
      read *,x
c      print *,x
c
c  find memberships of L and R halves
c
c
      do 2500 k=1,200
      if (ck(k). le. 0.0)go to 2600
      kk1=2*k-1
      kk2=2*k
      y(kk1)=x+rint*(k-1)*x
      y(kk2)=x-rint*(k-1)*x
2500  continue
c
2600  continue
      kmax=k
      ymax=x+rint*(kmax-1)*x
      ymin=x-rint*(kmax-1)*x
c
c  select standard scale of 25 - 3000
c
      do 2800 il=1,120
      z(il)=0.0
      mu(il)=0.0
2800  continue
c
      do 4000 il=1,120
      z(il)=3025-il*25.0
      if (z(il). gt. ymax) go to 4000
      if (z(il). lt. ymin) go to 4100
      do 3600 k=1,kmax
      kk1=2*k-1
      kk2=2*k
      test=rint*x*0.5
      if (abs(z(il)-y(kk1)). gt. test)go to 3000
      mu(il)=ck(k)
      go to 4000
3000  if (abs(z(il)-y(kk2)). gt. test)go to 3600
      mu(il)=ck(k)
      go to 4000
3600  continue
4000  continue
4100  continue
c
c
      return
      end

```

Skid.f

```

c This program is used to :
c   i. fuzzify the friction number for variations in temperature
c      and rainfall.
c   ii. fuzzify the friction number for variations in vehicle speed.
c
c
c
c      implicit real(a-z)
c      dimension k1(50),k2(50),ck(205),z(105),y(205),mu(105)
c      integer i,j,k,m,n,ii,jj,kk,nn,il,kk1,kk2
c
c Read the input data : i. number of data sets
c                      ii. percent ranges of variation
c                      iii. number of intervals for discretization
c
c      read *,nn
c      read *,r1,r2,n
c      an=n-1
c      rint=r1/an
c
c Initialization
c
c      do 100 i=1,n
c      k1(i)=0.0
100  continue
c
c      do 200 k=1,200
c      ck(k)=0.0
c      y(k)=0.0
200  continue
c
c      do 250 il=1,100
c      z(il)=0.0
c      mu(il)=0.0
250  continue
c
c Assigning of membership values to the kernels.
c
c      do 500 i=1,n
c      rri=(i-1)*rint
c      if (rri. gt. 0.5*r1)go to 300
c      k1(i)=1-2*((rri/r1)**2)
c      go to 500
300  k1(i)=2*((rri-r1)/r1)**2
500  continue
c
c      do 1000 j=1,50
c      rr2=(j-1)*rint
c      if (rr2. gt. r2)go to 1100
c      if (rr2. gt. 0.5*r2)go to 800
c      k2(j)=1-2*((rr2/r2)**2)

```

```

      go to 1000
800   k2(j)=2*((rr2-r2)/r2)**2)
1000  continue
c
1100  m=j
      do 2000 i=1,n
          ii=i-1
          do 1800 j=1,m
              jj=j-1
              kk=ii+jj
              k=kk+1
              k12=k1(i)*k2(j)
              if (ck(k). gt. k12) go to 1300
              ck(k)=k12
1300  continue
c
      if (ii. gt. jj)go to 1400
      kk=jj-ii
      go to 1500
1400  kk=ii-jj
1500  continue
      if (ck(k). gt. k12)go to 1800
      ck(k)=k12
1800  continue
2000  continue
c
c   Read input friction numbers
c
      do 5000 l=1,nn
          read *,x
c
c   Write fuzzified friction numbers
c
      write (6,7000)
c
      do 2500 k=1,200
          if (ck(k). le. 0.0)go to 2600
          kk1=2*k-1
          kk2=2*k
          y(kk1)=x+rint*(k-1)*x
          y(kk2)=x-rint*(k-1)*x
          write (6,7500) y(kk1),y(kk2), ck(k)
2500  continue
c
2600  continue
      kmax=k
      ymax=x+rint*(kmax-1)*x
      ymin=x-rint*(kmax-1)*x
c
      do 4000 il=1,100
          z(il)=101-il
          if (z(il). gt. ymax) go to 4000
          if (z(il). lt. ymin) go to 4100

```

```

do 3600 k=1,kmax
  kkl=2*k-1
  kk2=2*k
  test=rint*x*0.5
  if (abs(z(il)-y(kkl)). gt. test)go to 3000
  mu(il)=ck(k)
  go to 4000
3000  if (abs(z(il)-y(kk2)). gt. test)go to 3600
      mu(il)=ck(k)
      go to 4000
3600  continue
4000  continue
4100  continue
c
      do 4500 il=1,100
      z(il)=101-il
      if (mu(il). lt. 0.01)go to 4500
      write(6,8000) z(il),mu(il)
4500  continue
c
5000  continue
c
c
7000  format(4x,'value',7x,'membership',/)
7500  format(3x,f6.3,5x,f6.3,5x,f6.3)
8000  format(/,2x,f6.3,7x,f6.3)
c
      stop
      end

```

Dist.f

```

sp
c This program is used to :
c   i. fuzzify relevant distress ratings for imprecision associated with
c      the extent measurement.
c   ii. fuzzify relevant distress ratings for the subjectivity involved
c       in severity determination.
c   iii. manipulate a fuzzy PCR for each pavement section,
c        for FLEXIBLE pavements.
c
c       PCR = 100 - sum ( distress ratings )
c       (* Memberships of supports exceeding 100.0 are truncated.)
c
c
c
c       implicit real(a-z)
c       dimension r1(13),r2(13),k1(50),k2(50),y(205),z1(105)
c       dimension ck(205,13),z(105,13),mu(105,13),mus(105,13)
c       integer i,j,k,l,m,n,ii,jj,kkl,kk2,jjj,il,nd,np,icount
c
c Read the number of distress types and number of intervals
c
c       read *,nd,n
c       an=n-1
c
c
c Read the ranges of imprecision and subjectivity
c       (Note: 1. if distress type has neither imprecision
c              nor subjectivity use zeros.
c              2. if distress type has only one of the above
c              treat it as rl.
c
c
c       do 100 i=1,nd
c       read *,r1(i),r2(i)
100  continue
c
c Initialization
c
c       do 150 j=1,n
c       k1(j)=0.0
150  continue
c
c       do 200 k=1,200
c       y(k)=0.0
c       do 180 j=1,nd
c       ck(k,j)=0.0
180  continue
200  continue
c
c       do 300 il=1,100
c       z1(il)=0.0
c       do 250 j=1,nd
c       z(il,j)=0.0
250  continue

```

```

300    continue
c
c
c    Assigning of membership values to the kernels.
c
      do 2200 j=1,nd
        int=r1(j)/an
        do 500 i=1,n
          rrl=(i-1)*int
          if (r1(j). ne. 0.0)go to 350
          k1(i)=1.0
          go to 600
350      if (rr1. gt. 0.5*r1(j))go to 400
          k1(i)=1-2*((rr1/r1(j))**2)
          go to 500
400      k1(i)=2*(((rr1-r1(j))/r1(j))**2)
500      continue
c
600    continue
      do 1000 jj=1,50
        rr2=(jj-1)*int
        if (r2(j). ne. 0.0)go to 750
        k2(jj)=1.0
        go to 1100
750      if (rr2. gt. r2(j))go to 1100
          if (rr2. gt. 0.5*r2(j))go to 800
          k2(jj)=1-2*((rr2/r2(j))**2)
          go to 1000
800      k2(jj)=2*(((rr2-r2(j))/r2(j))**2)
1000     continue
c
1100    m=jj
      do 2000 i=1,n
        ii=i-1
        do 1800 jj=1,m
          jjj=jj-1
          kk=ii+jjj
          k=kk+1
          k12=k1(i)*k2(jj)
          if (ck(k,j). gt. k12) go to 1300
          ck(k,j)=k12
1300      continue
c
          if (ii. gt. jjj)go to 1400
          kk=jjj-ii
          go to 1500
1400      kk=ii-jjj
1500      continue
          if (ck(k,j). gt. k12)go to 1800
          ck(k,j)=k12
1800      continue
2000      continue
2200      continue

```

```

c
    1count=0
c
c   Read the number of pavement sections
c
    read *,np
2300  continue
c
    do 2400 i1=1,100
    do 2350 j=1,nd
    mu(i1,j)=0.0
    mus(i1,j)=0.0
2350  continue
2400  continue
c
    1count=1count+1
    write(6,8000)1count
c
    do 5000 j=1,nd
    read *,x
c
    do 2500 k=1,200
    if (ck(k,j). le. 0.0)go to 2600
    kk1=2*k-1
    kk2=2*k
    y(kk1)=x+int*(k-1)*x
    y(kk2)=x-int*(k-1)*x
2500  continue
c
2600  continue
    kmax=k
    ymax=x+int*(kmax-1)*x
    ymin=x-int*(kmax-1)*x
c
    do 4000 i1=1,101
    z(i1,j)=101-i1
    if (z(i1,j). gt. ymax)go to 4000
    if (z(i1,j). lt. ymin)go to 4100
    do 3600 k=1,kmax
    kk1=2*k-1
    kk2=2*k
    test=int*x*0.5
    if (abs(z(i1,j)-y(kk1))). gt. test)go to 3000
    mu(i1,j)=ck(k,j)
    go to 4000
3000  if (abs(z(i1,j)-y(kk2))). gt. test)go to 3600
    mu(i1,j)=ck(k,j)
    go to 4000
3600  continue
4000  continue
4100  continue
c
    do 4500 i=1,101

```

```

      z1(i)=101-i
      do 4400 k=1,101
      if (mu(k,j). lt. 0.001)go to 4400
      if (j. gt. 1)go to 4150
      mus(k,j)=mu(k,j)
      go to 4400
4150  diff=z1(i)-z(k,j)
      if (diff. lt. 0.0)go to 4400
c
      do 4300 l=1,101
      zp=101-l
      jj=j-1
      if (mus(l,jj). lt. 0.001)go to 4300
      if (diff. ne. zp)go to 4300
      if (mu(k,j). gt. mus(l,jj))go to 4200
      mup=mu(k,j)
      go to 4210
4200  mup=mus(l,jj)
4210  if (mus(i,j). gt. mup)go to 4250
      mus(i,j)=mup
4250  continue
      go to 4400
4300  continue
4400  continue
      if (j. eq. 1)go to 4600
4500  continue
4600  continue
c
5000  continue
c
      write (6,7000)
      do 6000 i=1,101
      z1(i)=i-1
      if (mus(i,nd). lt. 0.001)go to 6000
      write(6,7500)z1(i),mus(i,nd)
6000  continue
c
      if (icount. lt. np)go to 2300
c
7000  format(5x,'PCR',8x,'membership',/)
7500  format(2x,f6.2,10x,f6.3)
8000  format(///,'pavement section no.',15,/)
c
      stop
      end

```

Dm.f

```

c
c This program is used to ;
c     1. obtain the fuzzy priorities from attribute values
c     2. rank the fuzzy priorities
c
c
c     Implicit real (a-z)
c     dimension nav(3),mu(1000),mumax(105),mus(50,105)
c     dimension suput(50),ut(105),bb(50,20),db(50,20),mut(1000,105)
c     dimension at(3,50),aat(3),atmu(3,50),uut(20),duut(20)
c     integer i,j,k,kl,k2,k3,l,n,m,ii,nt,nav,ne
c
c Read the number of pavement sections
c
c     read *,n
c
c Read attribute values
c
c     do 5000 i=1,n
c
c     do 200 j=1,3
c
c     read *,nav(j)
c
c     do 100 k=1,nav(j)
c     read *, at(j,k),atmu(j,k)
100 continue
c
200 continue
c
c Form attribute tuples
c
c     nt=nav(1)*nav(2)*nav(3)
c
c     ii=1
c
c     do 1000 kl=1,nav(1)
c     mu(ii)=atmu(1,kl)
c     do 800 k2=1,nav(2)
c     if (k2. eq. 1) dum2=mu(ii)
c     if (k2. gt. 1) mu(ii)=dum2
c     if (mu(ii). lt. atmu(2,k2)) go to 500
c     mu(ii)=atmu(2,k2)
500 continue
c     do 600 k3=1,nav(3)
c     if (k3. eq. 1) dum1=mu(ii)
c     if (k3. gt. 1) mu(ii)=dum1
c     if (mu(ii). lt. atmu(3,k3)) go to 550
c     mu(ii)=atmu(3,k3)
550 continue
c

```

```

        ii=ii+1
600    continue
800    continue
1000   continue
c
c    Obtain the corresponding utilities
c
        suput(i)=1.0
c
        ii=1
c
        do 2000 k1=1,nav(1)
        do 1800 k2=1,nav(2)
        do 1600 k3=1,nav(3)
c
        aat(1)=at(1,k1)
        aat(2)=at(2,k2)
        aat(3)=at(3,k3)
c
        call interpol(ii,uut,duut,ne,aat,i,db,bb,m)
c
c    obtain the fuzzy utilities
c
        call fuzzut(uut,duut,ii,ne,ut,mut)
c
c
        ii=ii+1
1600   continue
1800   continue
2000   continue
c
c
        do 2400 l=1,91
c
c    Initialize
c
        mus(i,1)=0.0
c
c    Obtain a fuzzy priority value for the section
c
        do 2300 ii=1,nt
c
        if (mut(ii,1). eq. 0.0) go to 2100
        if (suput(i). gt. ut(1)) go to 2100
c
        suput(i)=ut(1)
2100   continue
c
        if (mut(ii,1). lt. mu(ii)) go to 2200
        dum=mu(ii)
        go to 2250
2200   dum=mut(ii,1)
2250   continue

```

```

c
      if (mus(i,1). gt. dum) go to 2300
      mus(i,1)=dum
c
2300  continue
2400  continue
c
5000  continue
c
c  Form the maximizing set
c
      supp=0.0
c
      do 6000 i=1,n
      if (supp. gt. suput(i)) go to 6000
      supp=suput(i)
6000  continue
c
      do 7000 l=1,91
      if (ut(l). gt. supp) go to 7100
      mumax(l)=ut(l)/supp
7000  continue
7100  continue
c
c  Calculate a relative rank for the section
c
      write(6,8400)
8400  format('section',3x,'rel. priority',///)
c
      do 9500 i=1,n
c
      opt=0.0
c
      do 9000 l=1,91
      if (mus(i,1). lt. mumax(l)) go to 8500
      mus(i,1)=mumax(l)
8500  continue
      if (opt. gt. mus(i,1)) go to 9000
      opt =mus(i,1)
c
9000  continue
c
      write (6,9100)i,opt
9100  format(2x,i5,x,f10.3,/)
c
9500  continue
c
      stop
      end
c
c
c
      subroutine interpol(ii,uut,duut,ne,aat,i,db,bb,n)

```

```

c
c   Given the attribute values, this subroutine calculates
c   the corresponding relative priority of the section.
c
      implicit real (a-z)
      dimension aat(3),utst(20,50),wkarea(50),dutst(20,50),bb(50,20)
      dimension atst(3,50),a(50,50),b(50,1),db(50,20),uut(20),duut(20)
      integer ii,i,nn,n,ne,k,kk,j,jj,l,ll,m,ia,idgt,ier

c   Read utilities provided by experts and the corresponding
c   attribute values.
c
      if (ii. gt. 1) go to 130
      if (i. gt. 1) go to 130

c
      read *,n,ne

c
      nn=3*n+1
      m=1
      idgt=0
      ia=50

c
      do 100 k=1,nn
        read *,atst(1,k),atst(2,k),atst(3,k)
100    continue

c
      do 125 k=1,nn
        do 110 l=1,ne
          read *,utst(1,k),dutst(1,k)
110    continue
125    continue
130    continue

c
c
      do 1800 l=1,ne

c
      ll=1
150    continue
      if (ii. gt. 1) go to 1100
      if (i. gt. 1) go to 1100

c
      do 300 k=1,nn

c
      if (ll. eq. 1) b(k,1)=utst(1,k)
      if (ll. eq. 2) b(k,1)=dutst(1,k)
      a(k,1)=1.0

c
      do 200 j=1,n

c
      jj=3*j-1
      a(k,jj)=atst(1,k)**j
      a(k,jj+1)=1.0/(atst(2,k)**j)
      a(k,jj+2)=1.0/(atst(3,k)**j)

```

```

c
200    continue
300    continue
c
c  Solve the set of 3n+1 simultaneous equations
c  and store the solution in b vector.
c
      call leqtlf (a,m,nn,ia,b,idgt,wkarea,ier)
c
c  Find the utility corresponding to the attributes
c  given in the main program
c
c
      do 1000 k=1,nn
      if (ll. eq. 1) bb(k,1)=b(k,1)
      if (ll. eq. 2) db(k,1)=b(k,1)
1000    continue
1100    continue
c
      if (ll. eq. 1) aut=bb(1,1)
      if (ll. eq. 2) autl=db(1,1)
c
      do 1300 k=1,n
      kk=3*k-1
c
      aut=aut+bb(kk,1)*(aat(1)**k)
      aut=aut+bb(kk+1,1)/(aat(2)**k)
      aut=aut+bb(kk+2,1)/(aat(3)**k)
      autl=autl+db(kk,1)*(aat(1)**k)
      autl=autl+db(kk+1,1)/(aat(2)**k)
      autl=autl+db(kk+2,1)/(aat(3)**k)
1300    continue
c
      if (ll.eq. 2) go to 1500
      uut(1)=aut
      go to 1600
1500    duut(1)=autl
c
1600    continue
      if (ll. eq. 2) go to 1800
      ll=2
      go to 150
1800    continue
c
      return
      end
c
c
c
      subroutine fuzzut(uut,duut,ii,ne,ut,mu)
c
c  This subroutine calculates the fuzzy utilities, given
c  the assigned utilities and the ranges of each expert.

```

```

c      implicit real (a-z)
      dimension uut(20),duut(20),ut(105),mut(1000,105)
      integer ii,ne,ll,l
c
c      Initialization
c
      do 100 ll=1,91
        mut(ii,ll)=0.0
100    continue
c
      do 1000 l=1,ne
        do 500 ll=1,91
c
c      Use a standard interval for utilities
c
          ut(ll)=1.0+(ll-1)*0.1
          if (ut(ll). lt. uut(l)) go to 500
          if (ut(ll). gt. (uut(l)+duut(l))) go to 500
c
          mut(ii,ll)=mut(ii,ll)+1
c
500    continue
1000   continue
c
      do 1500 ll=1,91
        if (mut(ii,ll). eq. 0.0) go to 1500
        mut(ii,ll)=mut(ii,ll)/ne
1500   continue
c
      return
      end

```

Pslife.f

```

c Program to evaluate the PSI life of a pavement section
c and to calculate the fuzzy life for it.
c
    implicit real (a-z)
    dimension pr(44),up(44),tt(44),tu(44)
    dimension xtprime(750),ytprime(750)
    dimension xuprime(750),yuprime(750)
    dimension mupr(44),muup(44),muat(750)
    dimension pt(900),wt(900),d(900),tres(44),p(40),b(900)
    integer t,i,j,k,jj,m,npav,l,n
c
c Open files for plotting
c
    open (unit =1 , file =`life` , status = `old`)
    open (unit =2 , file =`memb` , status = `old`)
c
c Read number of pavements
c
    read *,npav
c
c Unacceptable performance level (PSI)
c
    do 200 j=1,44
    read *, up(j), muup(j)
    if (muup(j).lt. 0.0001) go to 210
c    print *, `UP`,up(j),`MUUP`,muup(j)
200 continue
210 continue
c
    do 2000 m=1,npav
    l=0
c
c Read Structural Number
c
    read *, sn
c
    beta= 1.00 + 1.624*(10.0**7.0)/((sn+1.0)**8.46)
    alogro= 7.35*log10(sn+1.0) - 0.06
    print *,sn,beta,alogro
c
c Read ADT,% Trucks,Axial load/Truck,yearly inc. in traffic (%)
c # of years to evaluate PSI life,construction year.
c
    read *,adt,tr,r,ainc,t,time
c
    timel=1982.0-time
    do 300 i=1,t
    adt0=adt/((1.0+ainc)**timel)
    esal= adt0*tr*r
    a=float(i)/10.0
    wt(i)=365.0*esal*(((1.0+ainc)**a)/(log(1.0+ainc)))-

```

```

$ 1.0/(log(1.0+ainc)))
  pt(i)= 4.5 - 10.0**(log10(3.0) + beta*(log10(wt(i))-
$ alogro))
  if (pt(i).lt.0.0) go to 300
c      print *, a,pt(i),wt(i)
300      continue
c
      do 400 j=1,44
      p(j)=4.5-0.1*j
      do 500 i=1,t
      b(i)=float(i)/10.0
      d(i)=abs(pt(i) - p(j))
      if (d(i-1).eq.0.0) go to 500
      if (d(i).gt.d(i-1)) then
      tres(j)=b(i-1)
c600      print *, 'tres=', tres(j), 'psi=', p(j)
      go to 400
      endif
500      continue
400      continue
c
c      Present performance level (PSI)
c
      do 100 j=1,44
      read *, pr(j), mupr(j)
      if (mupr(j).lt. 0.0001) go to 110
c      print *, 'PR',pr(j), 'MUPR',mupr(j)
100      continue
110      continue
c
c      Calculate times corresponding to present
c      and unacceptable levels
c
      do 700 i=1,44
      pl=4.5-(i/10.0)
      do 800 j=1,44
      if (abs(pr(j)-pl).lt.0.0001) then
      tt(j)=tres(i)
c      print *, 'j',j, 'ttj',tt(j),mupr(j)
      endif
800      continue
      do 900 j=1,44
      if (abs(pl- up(j)).lt.0.0001) then
      tu(j)=tres(i)
c      print *, 'j',j, 'tuj',tu(j),muup(j)
      endif
900      continue
700      continue
c
c      do 950 j=1,44
c      print *,j, 'TT',tt(j), 'PR',pr(j),mupr(j), 'TU',tu(j),
c      $ 'UP',up(j),muup(j)

```

```

c950    continue
c
c      Interpolation
c
      do 960 j=1,44
      if (tt(j+1).eq.0.0) go to 960
      dxt=tt(j)-tt(j+1)
      if (dxt.lt.0.0) go to 960
      dyu=mupr(j+1)-mupr(j)
      sl=dyu/dxt
      n=ifix(dxt*10.0+0.5)
c      print *, dxt,dyu,sl,n
      do 970 i=1,n
      l=l+1
      xtprime(l)=tt(j)-float((i-1)/10.0)
      ytprime(l)=mupr(j)+sl*float((i-1)/10.0)
c      print *,l,xtprime(l),ytprime(l)
c970    continue
c960    continue
c
      l=0
      do 980 j=1,44
      if (tu(j+1).eq.0.0) go to 980
      dxt=tu(j)-tu(j+1)
      if (dxt .lt. 0.0) go to 980
      dyu=muup(j+1)-muup(j)
      sl=dyu/dxt
      n=ifix(dxt*10.0+0.5)
c      print *, dxt,dyu,sl,n
      do 990 i=1,n
      l=l+1
      xuprime(l)=tu(j)-float((i-1)/10.0)
      yuprime(l)=muup(j)+sl*float((i-1)/10.0)
c      print *,l,xuprime(l),yuprime(l)
c990    continue
c980    continue
c
c      do 1110 k=1,250
c      print *,k,xtprime(k),ytprime(k),xuprime(k),yuprime(k)
c1110   continue
c
c      Calculate the fuzzy serviceability life
c
      do 1000 jj=1,250
      do 1100 j=1,250
      if (xtprime(j).eq.0.0.and.xuprime(j).eq.0.0) then
      go to 1000
      endif
      tk=xuprime(jj)-xtprime(j)
      if (tk. le. 0.0) go to 1100
      mu =yuprime(jj)
      if (mu. lt. ytprime(j)) go to 1200
      mu = ytprime(j)

```

```

1200    continue
c
      do 1300 k=1,750
      kk=k/10.0
      if (abs(tk-kk). gt. 0.05) go to 1300
      if (mu. lt. muat(k)) go to 1300
      muat(k)=mu
1300    continue
1100    continue
1000    continue
c
c      Print the fuzzy serviceability life
c
      print *,`
      print *,`Section No.=`,m
      print *,`PSI Life`,`Membership`
      print *,`
c
      do 1400 k=1,750
      kk=k/10.0
      if (muat(k). lt. 0.01) go to 1400
      write (1,*) kk
      write (2,*) muat(k)
      write(6,1500) kk,muat(k)
1400    continue
1500    format(2f8.3)
c
      write (1,*) `III`
      write (2,*) `III`
c
      do 1600 k=1,750
      muat(k)=0.0
      xtprime(k)=0.0
      ytprime(k)=0.0
      xuprime(k)=0.0
      yuprime(k)=0.0
1600    continue
c
      do 1700 k=1,44
      tu(k)=0.0
      tt(k)=0.0
      mupr(k)=0.0
      pr(k)=0.0
      continue
1700    mu=0.0
      kk=0.0
      tk=0.0
      pl=0.0
      esal=0.0
      a=0.0
c
      do 1800 k=1,t
      wt(k)=0.0

```

```

      pt(k)=0.0
      b(k)=0.0
      d(k)=0.0
1800   continue
c
      do 1900 k=1,44
      p(k)=0.0
      tres(k)=0.0
1900   continue
c
2000  continue
c
c      Close plotting files
c
c      close (unit=1, status="keep")
c      close (unit=2, status="keep")
c
c      stop
c      end
```

Flife.f

```

c   Program to evaluate friction performance
c
c       implicit real (a-z)
c       dimension xl(1750),fn(1750),ad(1750),adt(1750)
c       dimension f(152),b(1750),d(1750),tres(152)
c       dimension xtprime(750),ytprime(750)
c       dimension xuprime(750),yuprime(750)
c       dimension pr(40),up(40),tt(1750),tu(1750)
c       dimension mupr(40),muup(40),muat(500)
c       integer t,i,j,k,jj,m,npav,n,l
c
c       read *,b0,b1,t
c       read *,npav
c
c       Unacceptable friction level (FN)
c
c       do 200 j=1,40
c       read *, up(j), muup(j)
c       if (muup(j).lt. 0.0001) go to 210
c       print *, "UP",up(j),"MUUP",muup(j)
c       continue
200  continue
c
c
c       do 2000 m=1,npav
c       l=0
c
c       Read ADT, % incr. in ADT, constr. year.
c
c       read *,adt1,ainc,time
c       timel=1982.0-time
c       adt0=adt1/((1.0+ainc)**timel)
c
c       do 10 i=1,t
c       adt(i)=365.0*adt0*((1.0+ainc)**(i-1))
c       adt(i)=adt(i)+adt(i-1)
c       xl(i)=alog10(adt(i))
c       fn(i)=b0+b1*xl(i)
10  continue
c
c       do 20 i=1,t
c       if (fn(i).lt.0.0) go to 20
c       print *, "t=",i,"years", "FN=",fn(i),"ADT",adt(i)
c20  continue
c
c
c       do 30 j=2,115
c       f(j)=116.0-j
c       do 40 i=1,t
c       b(i)=float(i)
c       d(i)=abs(fn(i)-f(j))

```

```

        if (d(i-1).eq.0.0) go to 40
        if (d(i).gt.d(i-1)) then
            tres(j)=b(i-1)
c35      print *,j,"tres=",tres(j),"fn=",f(j)
            go to 30
        endif
40      continue
30      continue
c
c      Present friction level (FN)
c
        do 100 j=1,40
            read *, pr(j), mupr(j)
            if (mupr(j).lt. 0.0001) go to 110
c          print *, "PR",pr(j),"MUPR",mupr(j)
100      continue
110      continue
c
c      Calculate times corresponding to present
c      and unacceptable levels
c
        do 700 i=2,115
            pl=116.0-float(i)
            print *,pl
c          do 800 j=1,40
                if (abs(pr(j)-pl).lt.0.0001) then
c              print *, "pr",pr(j),"pl",pl
                    tt(j)=tres(i)
c              print *, "j",j,"ttj",tt(j),mupr(j)
                    endif
800      continue
                do 900 j=1,40
                    if (abs(pl- up(j)).lt.0.0001) then
                        tu(j)=tres(i)
c              print *, "j",j,"tuj",tu(j),muup(j)
                            endif
900      continue
700      continue
c
c          do 810 j=1,40
                print *,j,"TT",tt(j),"PR",pr(j),mupr(j),"TU",tu(j),
c              $ "UP",up(j),muup(j)
c810      continue
c
c
c      Interpolation
c
            do 820 j=1,40
                if (tt(j+1).eq.0.0) go to 820
                dxt=tt(j+1)-tt(j)
                if (dxt.eq.0.0) then
                    go to 820
                else

```

```

dyu=mupr(j+1)-mupr(j)
sl=dyu/dxt
n=ifix(dxt)
c   print *, dxt,dyu,sl,n
      do 830 i=1,n
        l=l+1
        xtprime(l)=tt(j)+float(i-1)
        ytprime(l)=mupr(j)+sl*float(i-1)
c   print *,l,xtprime(l),ytprime(l)
830   continue
      endif
820   continue
c
      l=0
      do 840 j=1,40
        if (tu(j+1).eq.0.0) go to 840
        dxt=tu(j)-tu(j+1)
        if (dxt .eq. 0.0) then
          go to 840
        else
          dyu=muup(j+1)-muup(j)
          sl=dyu/dxt
          n=ifix(dxt)
c   print *, dxt,dyu,sl,n
            do 850 i=1,n
              l=l+1
              xuprime(l)=tu(j)-float(i-1)
              yuprime(l)=muup(j)+sl*float(i-1)
c   print *,l,xuprime(l),yuprime(l)
850   continue
            endif
840   continue
c
      do 860 k=1,250
        if (xtprime(l).eq.0.0) then
          xtprime(l)=tt(l)
          ytprime(l)=1.0
        endif
        if (xuprime(l).eq.0.0) then
          xuprime(l)=tu(l)
          yuprime(l)=1.0
        endif
        if (xtprime(k).eq.0.0.and.xuprime(k).eq.0.0) go to 860
c   print *,k,xtprime(k),ytprime(k),xuprime(k),yuprime(k)
860   continue
c
c   Calculate the fuzzy friction life
c
      do 1000 jj=1,250
        do 1100 j=1,250
          if (xtprime(j).eq.0.0.and.xuprime(j).eq.0.0) then
            go to 1000
          else

```

```

tk=xuprime(jj)-xtprime(j)
if (tk. le. 0.0) go to 1100
mu =yuprime(jj)
if (mu. lt. ytprime(j)) go to 1200
mu = ytprime(j)
1200 continue
c
do 1300 k=1,250
if (abs(tk-k). gt. 0.05) go to 1300
if (mu. lt. muat(k)) go to 1300
muat(k)=mu
1300 continue
endif
1100 continue
1000 continue
c
c Print the fuzzy friction life
c
print *, ' '
print *, 'Section No.=',m
print *, 'FN Life', 'Membership'
print *, ' '
c
do 1400 k=1,250
if (muat(k). lt. 0.01) go to 1400
kk=float(k)
write(6,1500) kk,muat(k)
1400 continue
1500 format(2f8.3)
c
tk=0.0
mu=0.0
pl=0.0
do 1600 k=1,250
muat(k)=0.0
xtprime(k)=0.0
ytprime(k)=0.0
xuprime(k)=0.0
yuprime(k)=0.0
1600 continue
c
do 1700 k=1,40
muapr(k)=0.0
tu(k)=0.0
tt(k)=0.0
pr(k)=0.0
1700 continue
c
do 1800 k=2,115
f(k)=0.0
tres(k)=0.0
1800 continue
c

```

```
do 1900 k=1,t
  b(k)=0.0
  d(k)=0.0
  ad(k)=0.0
  adt(k)=0.0
  xl(k)=0.0
  fn(k)=0.0
1900  continue
c
2000  continue
      stop
      end
```


COVER DESIGN BY ALDO GIORGINI